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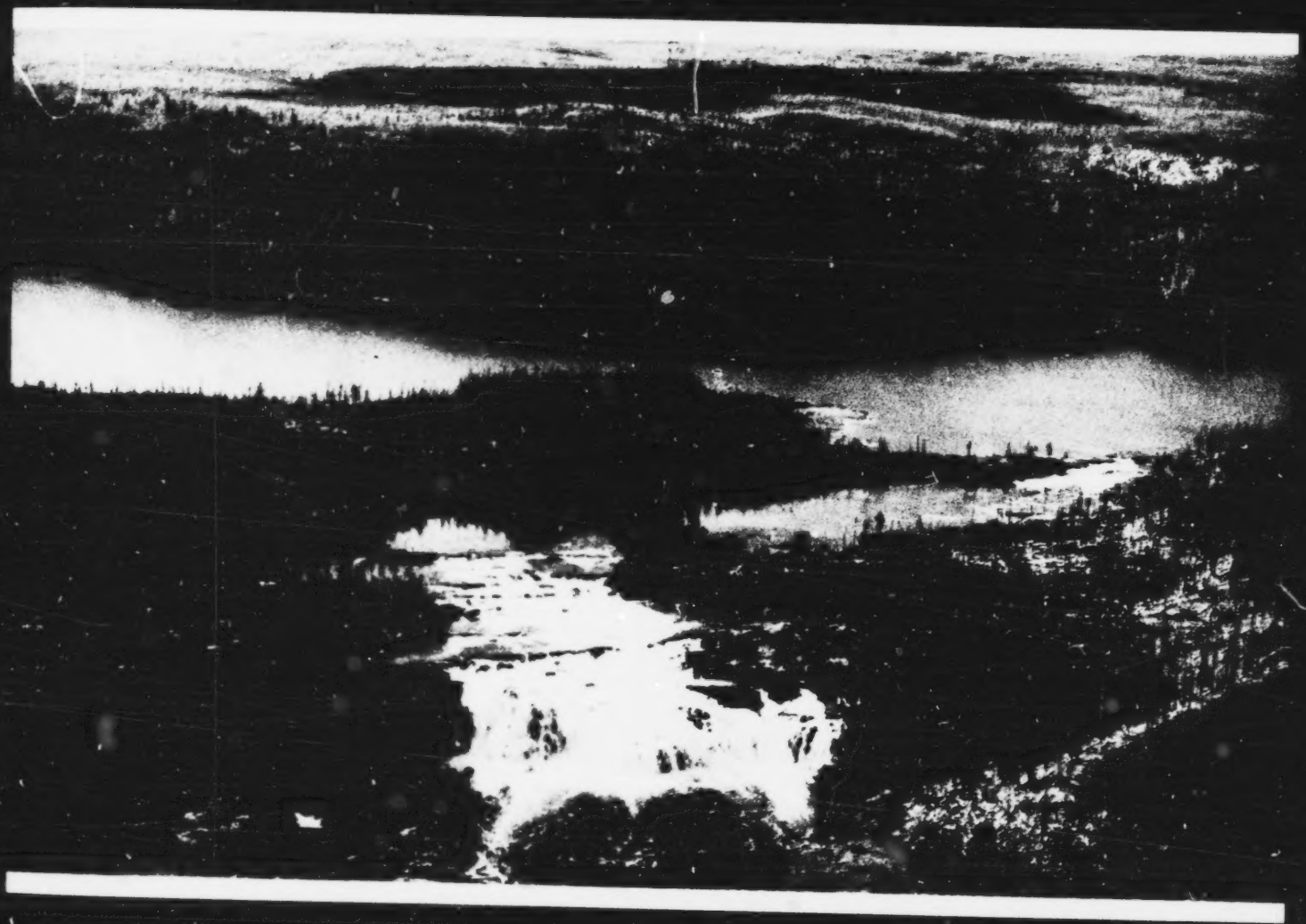
STREAMFLOW FORECASTING — Proceedings of the Technology Transfer Workshop

PRÉVISION DES DÉBITS — Comptes rendus de l'atelier sur l'échange d'informations d'ordre technologique



TECHNICAL WORKSHOP SERIES NO. 5
ÉTUDE N° 5, SÉRIE DES ATELIERS TECHNIQUES

INLAND WATERS DIRECTORATE
OTTAWA, CANADA, 1985

DIRECTION GÉNÉRALE DES EAUX INTÉRIEURES
OTTAWA, CANADA, 1985

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Cover photograph

Aerial view of Hunt Falls. Courtesy of Sask. Govt. Photo.

PROCEEDINGS

of the

TECHNOLOGY TRANSFER WORKSHOP

STREAMFLOW FORECASTING

Downsview, Ontario, November 22-24, 1983

TECHNICAL WORKSHOP SERIES NO. 5

COMPTES RENDUS

de

L'ATELIER SUR L'ECHANGE D'INFORMATIONS D'ORDRE TECHNOLOGIQUE

PREVISION DES DEBITS

Downsview (Ontario), 22 au 24 novembre 1983

ETUDE N° 5, SERIE DES ATELIERS TECHNIQUES

FOREWORD

The objective of this workshop was to improve the ability, efficiency and effectiveness of IWD, provincial and other agencies, to fulfil their responsibilities related to streamflow forecasting by:

- exchanging information between Canadian agencies on the various operational procedures in use across the country,
- exchanging information between various Canadian research and development groups on the emphasis in research programs,
- evaluating the usefulness of forecasts and identifying priorities in developing improved computational techniques,
- identifying priorities in the acquisition and improvement of scientific equipment.

Twenty background and four theme papers for the workshop were prepared in advance and distributed to attendees before the workshop. The papers will be taken as read. The first day and a quarter was devoted in plenary session to a brief presentation and discussion of these papers all of which were assumed to have been read by participants beforehand.

The workshop then broke into four working groups for in-depth discussion of the following subjects:

Working Group 1 - Meteorological Input to Forecasting

- equipment and network needs,
- use of radar and satellite imagery,
- possible computational improvements,
- compatability with needs of flow forecasting,
- data transmission.

Working Group 2 - Hydrometric Input to Forecasting

- equipment and network needs,
- possible improved measuring techniques,
- data transmission.

Working Group 3 - Computational Procedures

- models in use and under development,
- calibration, verification and evaluation,
- possible improved computational procedures,
- centralized versus distributed operations.

Working Group 4 - Management and Organization

- centralized versus distributed operations,
- data transmission and retrieval,
- dissemination of forecasts to:
  a) government agencies and utilities,
  b) public and the media,
- timing,
- staff, budget and organizational requirements.

A chairman and a rapporteur were assigned to each working group. The chairman led the discussion and, following the working group sessions, both participated in summarizing the presentation and discussions by preparing a short report which identified the issues, problems, gaps in knowledge, solutions, and recommendations. These were presented to plenary session on the third day. At the conclusion, the Workshop Chairman provided a summarizing "wrap-up" which combined the three working group reports with the plenary discussion, and developed a preliminary overview. These reports provided the basis for preparing the workshop Proceedings.

C. Officials

The Workshop Officials were the following:

Workshop Chairman	R.L. Pentland	IWD, Ottawa
Workshop Secretary	D.W. Farley	IWD, Ottawa
WG-1 Chairman	W.D. Hogg	AES, Downsview
Rapporteur	D.G. Schaefer	AES, Vancouver
WG-2 Chairman	S.K. Gupta	Ontario Hydro
Rapporteur	D.R. Kimmett	IWD, W&N Region
WG-3 Chairman	M.C. Quick	U.B.C.
Rapporteur	R.D. Hofer	IWD, W&N Region
WG-4 Chairman	J.G. Lockhart	N.B. Environment
Rapporteur	J. Robinson	IWD, Ontario Region

Sixty-one individuals attended the workshop representing federal agencies (30), provincial agencies (17), the private sector (8), and universities (6).

The Proceedings are divided into three parts. Part I is published in both French and English. It contains the reports of the working groups and the plenary session including the recommendations arising from the workshop. Part II is a compilation of the papers submitted in the language of the authors. Part III contains a listing of the names and addresses of attendees and of their participation in the four working groups.

AVANT-PROPOS

L'objectif de l'atelier était de faire en sorte que la DGEI et les organismes provinciaux et autres soient mieux à même de s'acquitter plus efficacement de leurs attributions de prévision des débits, par les moyens suivants:

- échanges d'information entre organismes canadiens sur les diverses modalités opérationnelles en usage au pays,

- échanges d'information entre divers groupes canadiens de recherche et de développement sur l'appui accordé aux programmes de recherche;

- évaluation de l'utilité des prévisions et identification des priorités relatives à la préparation de meilleures techniques de calcul,

- identification des priorités d'acquisition et d'amélioration du matériel scientifique.

Les participants ont reçu, au préalable, vingt documents de base et quatre thématiques. Les documents seront reçus tels qu'ils seront lus. Les participants devaient, au préalable, avoir pris connaissance des documents qui ont été présentés brièvement et discutés en plénière pendant la première journée et le quart de la suivante.

L'assemblée s'est ensuite répartie en quatre groupes de travail afin d'approfondir les questions suivantes:

Groupe de travail no 1 - Apport de la météorologie

- besoins touchant le matériel et le réseau,
- utilisation des images obtenues par radar et par satellite,
- perspectives d'amélioration des calculs,
- compatibilité avec les besoins de prévision des débits,
- transmission des données.

Groupe de travail no 2 - Apport de l'hydrométrie

- besoins touchant le matériel et le réseau,
- amélioration éventuelle des techniques de mesure,
- transmission des données.

Groupe de travail no 3 - Modalités de calcul

- modèles en usage ou à l'étude,
- étalonnage, vérification et évaluation,
- amélioration éventuelle des modalités de calcul,
- fonctionnement centralisé ou décentralisé.

Groupe de travail no 4 - Gestion et organisation

- fonctionnement centralisé ou décentralisé,
- transmission et extraction des données,
- diffusion des prévisions aux destinataires:
  a) organismes gouvernementaux et services publics,
  b) public et média,
- facteur temps,
- exigence en matière de budget, de personnel et d'organisation.

Un président et un rapporteur ont été nommés dans chaque groupe de travail. Le premier dirigeait les discussions et, après les séances, les deux préparaient un bref rapport dans lequel ils dégageaient les questions, les problèmes, les points obscurs, les solutions et les recommandations. Les rapports ont été présentés à la séance plénière du troisième jour. A la clôture, le président de l'atelier fit un résumé des trois rapports des groupes de travail exposés en plénière et d'après lesquels il tira provisoirement une conclusion globale. Les rapports ont servi à la préparation du compte rendu de l'atelier.

C. Responsables

Voici les responsables de l'atelier:

Président de l'atelier		R.L. Pentland	DGEI, Ottawa
Secrétaire de l'atelier		D.W. Farley	DGEI, Ottawa
GT-1:	Président	W.D. Hogg	SEA, Downsview
	Rapporteur	D.G. Schaefer	SEA, Vancouver
GT-2:	Président	S.K. Gupta	Hydro-Ontario
	Rapporteur	D.R. Kimmett	DGEI, Ouest et Nord
GT-3:	Président	M.C. Quick	Université de la C.-B.
	Rapporteur	R.D. Hofer	DGEI, Ouest et Nord
GT-4:	Président	J.G. Lockhart	Environnement N.-B.
	Rapporteur	J. Robinson	DGEI, Ontario

Les 61 participants représentaient des organismes fédéraux (30), des organismes provinciaux (17), le secteur privé (8) et les universités (6).

Le compte rendu comporte trois parties. La partie I est bilingue et contient les recommendations découlant de l'atelier et des rapports des groupes de travail et la plénière. La partie II contient une compilation des documents présentés dans la langue des auteurs. La liste des participants (noms et adresses) et la composition des quatre groupes de travail est présentée à la partie III du compte rendu.

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PART I

DISCUSSION SUMMARIES

INTRODUCTION

Welcome by Jim Bruce

Mr. Jim Bruce, Assistant Deputy Minister of the Atmospheric Environment Service (AES) of Environment Canada, welcomed the attendees to AES Headquarters in Downsview, Ontario. Mr. Bruce noted the recent advances in information technology, and discussed how AES was attempting to cope with increasing demands from users of meteorological data. He mentioned the recent acquisition by AES of the Cray super computer presently operating at the forecasting centre in Dorval, Quebec. The additional capability which this computer provides will make it possible to extend the time horizon of temperature and quantitative precipitation forecasts.

Background of this Initial Workshop on Streamflow Forecasting

Mr. Ralph Pentland, Director of the Water Planning and Management Branch, Inland Waters Directorate (IWD), Environment Canada, provided background information on this initial workshop, at the federal level, on streamflow forecasting.

When a workshop on streamflow forecasting was first proposed to the directors of IWD about one and a half years ago, the first inclination was to limit the workshop to employees of the Directorate. It was planned to simply have technical training and information sessions on procedures being used in streamflow forecasting with reference to various IWD involvements across the country. However, on closer examination of these involvements across the country, it was readily apparent that much of the operational work in streamflow forecasting was being carried out by other provincial and federal agencies and public utilities. The directors also suspected that IWD staff was more oriented towards flood forecasting and lacked a balanced view of other needs in forecasting such as for energy production, irrigation, biological and fisheries concerns, and recreation. IWD's U.S. colleagues stated that some of the major problems in streamflow forecasting in the U.S. involved management and organization.

After further deliberation on the subject, IWD contacted the other agencies and public utilities to see if they would support such a workshop which would involve their input. IWD obtained wide support from these organizations for this initiative and were provided with several comments on how to make the workshop more effective. Certain individuals in the private sector and the academic sector were also recommended to help give the workshop a balanced perspective. IWD is grateful for the support provided by these organizations, their commitment in providing papers and representatives, and the willingness of their representatives to take on several jobs at this workshop.

REPORT OF WORKING GROUP 1:
METEOROLOGICAL INPUT TO FORECASTING

Chairman: W.D. Hogg

Rapporteur: D.G. Schaefer

Exchange of Information

There was discussion on the transformation of Atmospheric Environment Service (AES) probability forecasts to quantitative precipitation forecasts. A procedure often used could be defined by the following equation:

$$QPF = AFR$$

where: QPF = quantitative precipitation forecast
F = fudge factor based on meteorological experience
R = average rain for a day in which rain occurs
A = step function

(if probability of precipitation $< 50\%$, $A=0$)

(if probability of precipitation $\geq 50\%$, $A=1$).

It was agreed that the AES quantitative precipitation forecasts are primarily useful in streamflow forecasting for flood warning and alert purposes, especially for small basins.

There is pressure on AES to design the interfaces between the data obtained in the large area synoptic weather forecasts and the data requirements for the usually much smaller watershed basins in which streamflow forecasting is conducted. There are simply too many watersheds with widely varying characteristics for AES to assume such tasks. AES does and will provide guidance to organizations in applying synoptic forecast data to watershed forecasting. However, the specific interface design for a particular basin can be best accomplished by meteorological expertise resident in the basin and closely associated with the streamflow forecasting operation.

Remote sensing by satellite and radar must remain an AES responsibility because of the large associated costs and the wide applicability of the data. Practical, faster and more efficient methods must be developed to merge remotely sensed data with conventional data before satellite and radar data can make a significant contribution to streamflow forecasting.

Stable meteorological databases are required. There should be improved communication concerning format changes, discontinuation of gauges, and relocation of radar sites. Regional hydrometeorological committees composed of major users should meet periodically. Minutes and newsletters should be sent to other users. Some regions already have such committees.

Priorities in Streamflow Forecasting Data Acquisition

The following data items are listed in order of priority for improving streamflow forecasts:

1. Temperature, precipitation and snowfall specified spatially and temporally;

2. Winter rain gauging requires improvement;

3. Difficulties should be resolved in measuring snow pack. Gauges tend to undercatch. There is now enough information to permit adequate adjustment of snow data in accordance with the biases;

4. Radiation for improved evapotranspiration estimates;

5. Precipitation determinations by radar requiring considerable resources for both equipment and computational approaches;

6. Wind data for determining evaporation, snowmelt, gauge corrections and ice jams.

With the growing number of data collection platforms (DCP's) installed throughout the country the feasibility of providing soil temperatures in real-time for identifying frozen ground should be investigated. Also, methods of measuring and acquiring real-time soil moisture data should be developed. Possibilities for soil moisture determination include measurements of magnetic resonance and gamma radiation, and remote sensing from satellites.

It was conceded that AES is lagging in the acquisition of data logging equipment. There are problems in achieving 30-second interval recordings of precipitation. This is a requirement for forecasting in very small catchments where the absolute fixation of the time of peak bursts of rainfall is important.

Low accuracy is being experienced to date in the quantitative determination of precipitation by radar. The use of radar seems to be most successful in identifying the spatial distribution of rainfall. Applications of the technique in Ontario have been successful. Alberta is now experimenting with radar. With the good communications generally available in Canada, more work must be done in merging recorded precipitation data with radar information. There was criticism that granting agencies are not making it possible for universities to develop the necessary software for accomplishing this task.

Research Priorities

The sensitivity of streamflow models to meteorological data should be defined. This could probably be best achieved by providing a range of basin scales with corresponding sensitivities for specific parameters.

There should be a concerted effort in providing confidence limits to estimated or measured meteorological data as well as forecasted data.

Work needs to be done in supplying improved estimates of snow cover. Data from snow courses are often not representative of actual snow cover. Extreme values of snow cover could probably be related to a mean depth in a watershed. Problems in estimating snow cover are more prevalent in prairie regions.

Present methods of estimating snow depletion are generally inadequate. A review should be carried out of existing snowmelt models with recommendations provided for application in basins of varying topographic relief.

Improvements are required in estimating lapse rates and variation in precipitation with elevation in mountainous regions.

Modular design should be incorporated in all modelling systems to permit flexibility and greater opportunities for improvement. The models and sub-routines should be physically sensible in the interests of portability and reliability for numerous users.

The most reliable and cost-effective methods for data transmission from data collection platforms (DCP's) should be determined. Presently, a lot of data are being lost in transmission. The meteor burst technique (wave propagation bounced off ionized trails in the upper atmosphere by meteors) appears to have the best potential in the far north. Data loss with the existing U.S. GOES satellite system occurs mostly on the ground between Wollops Island and the user. Downlink facilities in Downsview and at other Canadian sites could markedly improve the situation with respect to the receipt of GOES DCP data. Another possible alternative is through use of MSAT, the proposed Canadian satellite system. However, GOES does exist and does work. It is difficult to predict the performance of a system which does not yet exist.

REPORT OF WORKING GROUP 2
HYDROMETRIC INPUT TO FORECASTING

Chairman: S.K. Gupta

Rapporteur: D.R. Kimmett

Real-Time Systems

The group set out to determine what level of service is likely to be required in the future and the level of service that the Inland Waters Directorate (IWD) of Environment Canada is prepared to provide.

Current Problems in Implementation of Real-Time Systems

- The hardware technology is changing rapidly.
- The increasing number of types of data collection platforms (DCP's) creates problems in the acquisition and distribution of data.
- Differing DCP and computer hardware combined with a variety of formats creates technical training and management problems.
- There are different needs, knowledge base and levels of interest in different parts of the country.
- Several agencies expect to require, in the near future, several sensors attached to IWD DCP's.
- Using uncorrected or unverified real-time data can lead to problems in operational streamflow forecasting.
- Priority conflicts are emerging between real-time data users and operating agencies.
- There is a difficulty in merging data from old technology, such as telemarks, with data from new technology.
- There is a need for centralized data acquisition and dissemination at the regional level.

Current DCP Status and Issues

- IWD now has 95 DCP's. There is a total of about 350 DCP's in Canada.
- Newfoundland is just starting a real-time network and should advise the Canada/Newfoundland coordinating committee of its DCP needs.

- The latest version of DCP's provide for a wide variety of hydrological and meteorological sensors.

- IWD, for hydrometric purposes, has now developed a standard specification for DCP's used in Canada.

- A single agency for each DCP's registered with the National Environmental Satellite and Data Information Service (NESDIS) is responsible for maintaining the assigned radio transmitter band widths and transmission time slots as well as controlling access to the data in contrast to the use of landline equipment in which access is unlimited.

- Up to three secondary users can access DCP data through the use of formal identification codes.

- When a system goes down, users often demand immediate repair which may not be possible or even necessary.

Information Exchange and Questions on Real-Time Systems

- The current method of manually accessing real-time data from DCP's is inefficient.

- Several agencies would like centralized data acquisition, probably at the regional level, if cost effective.

- The Water Survey of Canada (WSC) is being asked to add task-oriented data collection to its historical role of inventory data collection.

- There is a need for standardized equipment and data formats.

- The resource problems and constraints may be resolved through cost recovery mechanisms.

- Some agencies want IWD to take the lead and make a firm commitment on real-time networks.

- How are IWD and AES going to collect and distribute the data?

- How is IWD going to handle requests for special sensors?

- Data management (storage, messaging, decoding) is regarded as an area requiring considerable development to meet current needs.

- The Ontario Ministry of Natural Resources (OMNR) would like to discuss data retrieval and handling of landline system data with WSC.

- If WSC managed the acquisition of data from DCP's, many of the problems currently being experienced with NESDIS would be reduced or eliminated.

- OMNR, Manitoba Water Resources Branch (MWRB) and Manitoba Hydro have decoded the Telemark audible signals using personal computers.

Recommendations:

1. IWD should work towards clarifying and standardizing the level of service it is willing to provide through policy statements as a follow-up to the January 1983 DOE "Policy on Services for Communication and Archiving of Data from Automatic Stations".

2. There should be a joint development of local operational guidelines and identification of costs associated with the level and type of service.

3. Programs for data acquisition and dissemination should be developed on a regional basis.

4. Automatic accessing equipment should be considered for obtaining digital information from telemark stations.

Sources of Errors

Stage-Discharge (S-D) Curves:

The forecaster has no choice but to use the S-D relationship during flood events even though it may not be valid. Conditions during floods often cause deviations from the S-D relationship. Flood forecasting agencies and WSC should meet at least once per year prior to break-up to identify priorities and to develop joint plans where feasible. WSC should also provide qualitative information to forecasting agencies on backwater effects created by unusual conditions such as ice jams and embankment failures. Other unusual conditions effecting flows and levels, such as natural diversions and beaver dam breaks, should also be noted.

Manual Observations Included in Historical Records:

It is recognized that manual observations which prevailed prior to 1960 can bias statistical analyses. However, most gauges prior to 1960 were on large basins where the definition of the response by one observation per day is often sufficient. If users are concerned with manual observations they should obtain copies of the gauge reader cards for review. Users are advised to always verify that they are using the latest updated version of data whether it be on magnetic tape, in microfiche, or on hard-copy.

Discharges Derived from Turbine and Spillway Rating Curves:

Spillway ratings are often affected by trash. Flows derived from turbine ratings tend to be less reliable than those measured by standard gauging procedures.

Ontario Hydro has an annual program routine of checking equipment and ratings. New Brunswick Power is in the process of adjusting its spillway rating coefficients in order that computed discharges will match WSC measurements.

Symbols:

The symbols B, E and A beside the data appear to be ignored by most users. These symbols would be more useful if they could be related to a degree of uncertainty. It was recommended that WSC attempt to provide confidence limits with its data.

REPORT OF WORKING GROUP 3: COMPUTATIONAL PROCEDURES

Chairman: M.C. Quick

Rapporteur: R.D. Hofer

Problems in Defining Accuracy and Adequacy

Members of the working group were reluctant to define the accuracy of the various forecasting models with which they were familiar. This reluctance was due to the fact that forecast accuracy is heavily dependent on the precision and adequacy of input data which are also difficult to define and vary widely temporally and spatially. Many models presently in use in Canada or proposed, were heavily criticized, but there was a concensus that forecasts were valuable, and that a model structure is required to integrate complex data sets for carrying out forecast analyses of watersheds, channels and storage systems.

Members were very concerned and preoccupied with the questions concerning input data, in particular: quality, the appropriateness or matching of data to the model being used, continuity and time distribution. Computational procedures incorporated in model design should match the data sets which will be available for real-time forecasting. During the present period of rapid advances in information technology, real-time data for many more parameters are being obtained or can be obtained at acceptable cost for given forecasting operations.

Classification of Models

The members agreed that the models used by their agencies could be classed under four types, namely: statistical, conceptual watershed, routing, and combinations of the above types.

Statistical:

Many statistical models are in use for seasonal forecasting ranging from quite short-term to long-term forecasts. These are primarily used when snowmelt forms a major input to runoff. Most use some form of antecedent moisture status of the watershed.

Some seasonal forecasts are based only on antecedent moisture and precipitation, and base flow.

Statistical models depend on a long data record measured in a similar manner at the same locations for many years. Statistical models are defined by sets of historical time series data at

prescribed locations and are therefore limited in application to these locations and pre-defined data sets. In contrast, a conceptual model can be adapted to use new data as they become available, and such models can be used to generate seasonal forecasts.

Some users claimed good results from statistical methods for short-term forecasts.

Several users reported that these seasonal statistical forecast models have a strong bias towards the long-term mean. However, even a conceptual model employed for seasonal forecasts must resort to climatology after a short time horizon of about five days resulting in forecasts approaching the mean as the time horizon is extended.

Statistical models have been used for forecasting both volume and peak flows. However, volume forecasts tend to be much more reliable than peak forecasts.

Conceptual Watershed:

Many conceptual models have too many parameters and fitting procedures are vague. Some users commented that similar model performance could be achieved with different sets of parameter values. This demonstrates the non-physical nature of some parameters.

Most models have such a complex, inter-related structure that individual processes cannot be easily separated. If processes could be separated, it would be possible to test model components and even to substitute new methods of modelling individual components. Consequently, modular design should be employed so that models can be adapted to new techniques and new data inputs.

A need for interactive capability in models was expressed. This capability would assist users in exploring parameter sensitivity as well as expediting calibration.

Routing:

Most routing is presently being carried out by means of hydrologic type models in which time of storage and backwater parameters are fitted to past observed events. Models such as SSARR, SIMPAK and Muskingum employ these methods. When there are complicated backwater conditions, complex hydraulic networks or tidal boundary conditions, hydrodynamic models are employed. These models employ topographic channel data, and require a data processing effort several times greater than that for the hydrologic type models. Members of the working group were not aware of an operational use in Canada of an in-between group of models referred to in the literature as kinematic wave and diffusion wave models. The existing routing models appear to be fully adequate given the existing problems in watershed modelling which yields the input to the routing models.

New Methods and Approaches

Rapidly advancing communications technology is making more data readily accessible over short time spans for a greater number of parameters at less cost. This technology is making it feasible to incorporate new routines or components in conceptual models. Probably the greatest need in these routines is to permit frequent and rapid updating. The working group also cautions that efficient methods must be incorporated with data acquisition for performing verification and reliability tests of data. Much of these frequently obtained data are expected to come from data collection platforms.

New data sources such as satellite imagery, radar precipitation estimates should be available on a very frequent (real-time) basis. Airborne gamma ray snow surveys will become more feasible for utilization on an infrequent basis. This information will need to be incorporated in the model structure and blended with other data inputs. Research is needed to investigate this amalgamation process, which is not a trivial question.

In many cases a regulation model is a necessity for forecasting. A watershed model with a simple routing algorithm is inadequate for a heavily regulated system of channels and reservoirs. There is a trend in incorporating operations research (optimization) techniques in regulation models. These techniques permit a decentralized but at the same time an integrated operation of the basin (holistic approach).

Research Needs

The non-physical nature of many model parameters and their relationships trouble users. Further research is needed to define the various processes involved in watershed behaviour. The following processes were especially identified as being of particular importance.

> Further research was recommended on snowmelt which is still mainly calculated using a degree-day approach. It was reported that an energy budget approach was more accurate on small, instrumented test basins, but on watersheds, especially on those exceeding 100 km^2, the degree-day method appeared to be slightly superior.
>
> Soil moisture presents several problems such as: determination of antecedent conditions, influence of soil frost and water infiltration. Soil frost was identified as a major problem for modelling runoff on the prairies with low snowpack. It was claimed that runoff from combined snowmelt and rainfall could vary from 10% to 90%, depending upon the amount of soil freezing and the rate of snowmelt.

Morton, in his paper at this workshop, notes several areas of research on soil moisture, evaporation, and ground water.

Further work to define the heat balance and ripening of snowpack is needed in order to forecast more reliably the onset of runoff from the snowpack. Peak flow forecasting for both prairie and high relief conditions is highly sensitive to the prediction of the onset of melt from the snowpack.

The conceptual watershed models need to be tested on good quality data derived from well-instrumented watersheds. It is felt that this is the only way in which effective progress can be made in improving model design and reliability. The economic return from new model features developed under this controlled testing is estimated to vary between 20 to 1 and 10 to 1. This good economic return to agencies in producing more accurate forecasts justifies the re-activation of IHD (International Hydrological Decade) research basins. Much of the IHD data has never been utilized, and little has been prepared for electronic data processing. A preliminary study is recommended for determining the feasibility of using this data.

REPORT OF WORKING GROUP 4: MANAGEMENT AND ORGANIZATION

Chairman: J.G. Lockhart

Rapporteur: J. Robinson

1. Institutional Framework and Organization

- The organizational structures of the New Brunswick, Manitoba, and Ontario forecast centres were reviewed.

- Because water is a provincial resource under the Constitution, the responsibility for flood forecasting should rest with the provinces. However, the responsibility for flood forecasting is not really well defined in some cases such as for international and interprovincial rivers.

- Each organizational structure has to be unique to address regional needs and circumstances. Different history, economic and social background necessitate a particular organization structure.

- It was generally agreed that there are certain advantages to a committee structure in providing expertise, data, technical support and communication. Some participants suggested that the U.S. National Weather System (NWS) is more efficient than Environment Canada in providing services to flood forecasting units. It was noted that NWS has responsibility for both weather forecasting and flood forecasting. It was further suggested by these participants that efficiency could be improved by merging AES and IWD.

- Federal government involvement is desirable when setting up forecast centres, but should be withdrawn when centres become fully operational.

- No change in the existing organization or responsibilities of the existing forecasting centres is recommended. However, there are certain areas (British Columbia and Quebec) where the responsibility for flood forecasting is not well defined due to reservoir operation by a utility and surveillance by a provincial government organization.

- There should be lead agencies on a regional or provincial basis with a mandate to provide streamflow forecasts.

2. Staff

Each agency reviewed its particular situation with respect to staffing and the following points were emphasized:

- The present staffing of the organizations studied was judged minimal for providing accurate and up-to-date flood flow and level forecasts.

- There is insufficient staff to provide back-up for year-round operations.

- Frequent training of staff and upgrading of expertise is essential. It was suggested that the course "Introduction to Hydrologic Principles" be revived by the Associate Committee on Hydrology of the National Research Council.

- Staff reductions are in some cases being compensated by automation as office technology advances.

- Good documentation of forecast methods and procedures is necessary for maintaining continuity in forecasts during staff turnover or long absences.

3. Communications

The following methods and technologies were reviewed: DCP's, telecopier, phone, AES circuits, code-a-phone, radar, auto dialer, switched data networks such as DATAPAC and INFODAT, computer terminals and microcomputers to access main frames via dial-in ports for automated data acquisition and electronic mail (pilot project under review by the Ontario Ministry of Natural Resources).

It was indicated that AES can transmit vast amounts of hydrometeorological and climatological data by dedicated communications circuits. This may be more cost effective than procedures currently in use.

More effective use should be made of flood risk maps, banks, real estate agents, and insurance companies in stressing to the public and municipal officials the need and value of flood forecasting.

Personal Communication:

At present there is little exchange between the streamflow forecasting centres. This meeting provided the first opportunity for representatives of the forecast centres to meet and discuss their operations.

The Group agreed that an annual or bi-annual meeting of representatives of the forecast centres should take place. The format of such meetings need not be formalized.

The Saint John River Forecast Centre volunteered to coordinate and host such a meeting in Fredericton. The suggested date was November 14-16, 1984, to coincide with a meeting of the Water Resources Working Group of the Canadian Advisory Committee on Remote Sensing (CACRS).

4. Data Collection

Data collection is currently being carried out by AES, WSC, provincial agencies and utilities. The types of data are generally: climatological, meteorological, hydrometric, and forecasts.

There is a need for sufficient data in real-time to ensure reliability of forecasts.

In the review of satellite imagery it was agreed that these data are useful for defining aerial snow cover. Unifax is a useful tool in providing weather information from satellites to the forecast centres.

Manitoba expressed a need for objective quantitative precipitation forecasts from AES that can be, if required, modified subjectively by users. This type of data would be more useful than probabilities of precipitation forecasts which have to be subjectively converted by the user to quantitative values.

Gamma snow surveys are being tested to provide snow/water equivalents. This technique may have definite applications in certain regions, however, the cost-effectiveness is questionable.

There is a need for radar data in New Brunswick and British Columbia. It was argued by some workshop attendees that the practicability of radar in mountainous terrain, such as in B.C., remains in doubt.

5. Forecast Production

The useful frequency of forecasts is dependant on the existing flood levels or the anticipated danger of flood levels. Hydro utilities generally require daily forecasts during freshet periods.

To date in Canada, probabilities are included in forecasts for only medium to long range forecasts in Manitoba and the Great Lakes.

6. Forecast Dissemination

Results of flood forecasts are provided to government agencies, utilities and the public by the following means:

- press releases to the media;
- telecopied to government and operating agencies;
- code-a-phone messages (updated as situation dictates);
- remote terminal access to forecasts stored on main frame computers;
- Emergency Measures Organization (EMO), alerts municipalities of the need for certain actions based on interpretation of flood forecasts for specific regions;
- the Conservation Authorities in Ontario provide much of the contact with municipalities who in turn contact the local public and the media.

A flood advisory or warning is preferable to "silence" or withholding forecast information due to uncertainty. However, caution must be exercised so as to not over-react and destroy the credibility of the forecasts.

The working group discussed the availability of "low cost" forecast techniques for small flashy streams where no forecasting is presently being done. It was suggested that the U.S. National Weather Service and other foreign organizations have developed simplified techniques to provide some useful flood warning systems.

It is recognized that, frequently, jurisdictional problems occur with regard to issuing forecasts at specific locations.

7. Finance and Budgets

The working group reviewed the cost-sharing agreements currently in effect in New Brunswick and Manitoba.

In order to justify streamflow forecasting costs, it is necessary to know the flood damages associated with a certain flood frequency. Methods used to date appear to be very inaccurate. A standardized system should be developed for identifying and estimating flood damage costs.

The resources applied to the forecasting effort should be related to the expected benefits. Cost/benefit procedures should be developed for justifying the cost of improvement of streamflow forecasts for a particular basin.

PLENARY SESSION

Comparative Organization Summary

The workshop chairman presented the following comparative organization summary for the 12 streamflow forecasting organizations represented at the workshop.

	No. of organizations
1. Organization	
- relatively separate centres	4
- regional offices	2
- integral part of organization	6
2. Purpose of Forecasts	
- multiple use	4
- flood forecasting	4
- flood forecasting hydro	2
- hydro	2
3. Distribution of Forecasts	
- general	8
- on-demand	2
- internal only	2
4. Runoff Model	
- custom design	5
- U.S. packages	4
- statistical	3
5. Routing	
- hydraulic and/or hydrodynamic	2
- hydrologic	7
- simple lag	3

Emerging Trends

The following list of emerging trends compiled by the chairman and secretary of the workshop was presented:

1) Quantitative meteorological forecasts are being extended from the present 2 days to 10 days in the near future.

2) Automation of data acquisition by means of DCP's, data loggers and other devices is being pursued by most streamflow forecasting agencies.

3) At least two organizations at the workshop are presently automatically entering meteorological and hydrometric data to their models. This trend is expected to continue with increasing requirements for effective data editing and verification algorithms.

4) Users are requesting and obtaining direct access to forecasts by such methods as code-a-phone and terminal access to disk files on main frames.

5) Contribution of radar data and satellite imagery has not lived up to expectations.

6) There is a decreasing fascination with "mathematics" which is being replaced by a fascination for "electronic" technology.

7) As computer literacy spreads there is a definite migration from the regression type models to the conceptual models.

8) There has been no evident progress during the last ten years in developing truly physically based models.

9) In built up areas with complicated hydraulic networks and backwater effects there is an increasing utilization and demand for hydrodynamic routing.

10) There is a tendency and an increasing demand to attach probabilities to forecasts.

11) There is an increasing recognition of the importance of frequent and rapid updating of conceptual models made possible by the on-going rapid advances in information technology.

12) Streamflow forecasting, like other federal and provincial government operations, is encountering fiscal restraints and demands of net benefits for an appropriate level of service.

RECOMMENDATIONS

The workshop chairman presented recommendations which were reviewed by all attendees. The recommendations were as follows:

1. There is a need for continuing information exchange between streamflow forecasting centres. (The Saint John River Forecasting Centre has offered to host a similar workshop next year in Fredericton.)

2. There is a need for regional hydrometeorological committees consisting of both originators and users of data.

3. The Associate Committee on Hydrology, or some other professional group, should consider:

   - a thorough review of old research information and recommendations for future conceptual approaches;
   - the reactivation of introductory training on hydrologic principles.

4. AES should better tailor its data products to streamflow forecasting needs with increased use of contemporary information technology.

5. IWD should clarify what level of service it is prepared to provide, and should document by region costs for various levels of service.

6. Research thrusts should take into account the following items:

   - fundamental research on physical processes;
   - more efficient ways to edit and introduce real-time data;
   - practical methods to merge radar data and/or satellite imagery with conventional data;
   - reduce loss of data in automated gathering techniques by considering other technical options such as meteor burst, MSAT;
   - intercomparison and evaluation of models used in Canada.

7. Model developers should consider:

   - modular approach and transportability to accommodate research advances;
   - optimization techniques to accommodate reservoir and channel network operations;
   - developing capability to automatically accept real-time data in order to rapidly and frequently update antecedent conditions;
   - developing "user friendly" models.

8. Both data collectors and modellers should work towards better definition of "expected error" and "confidence limits" for their products.

9. Forecast information should be integrated by reprographic techniques with flood risk maps, however caution must be exercised in how this information is presented to the public.

10. Financial evaluation techniques should be developed for economic justification of forecasts and for defining appropriate levels of service for identified needs.

PREMIERE PARTIE

SOMMAIRES DES DISCUSSIONS

INTRODUCTION

Bienvenue par Jim Bruce

M. Jim Bruce, sous-ministre adjoint du Service de l'environnement atmosphérique (SEA) d'Environnement Canada, accueillit les participants au centre administratif de SEA à Downsview, Ontario. M. Bruce remarqua les progrès récents dans l'informatique, et discuta comment SEA tentait de s'occuper des demandes croissantes des usagers des données météorologiques. Il mentionna la récente acquisition par SEA du super ordinateur Cray qui est en opération en ce moment à Dorval, Québec. La capacité additionnelle que cet ordinateur fournit va permettre d'étendre l'horizon de temps de la température et des pronostics quantitatifs de la précipitation.

Les antécédents de cet atelier initial sur la prévision de l'écoulement

M. Ralph Pentland, directeur de la Direction de la planification et de la gestion (eaux), Direction générale des eaux intérieures (DGEI), Environnement Canada, a fourni la documentation pour cet atelier initial, au niveau fédéral, sur la prévision de l'écoulement.

Quand on a tout d'abord proposé un atelier sur la prévision de l'écoulement aux directeurs de DGEI il y a un an et demi, la première idée a été de limiter l'atelier aux employés de la Direction générale. On avait pensé d'avoir seulement des sessions d'information et d'entraînement sur les techniques utilisées dans la prévision de l'écoulement avec référence aux différents rôles de DGEI à travers le pays. Cependant, en examinant de plus près ces engagements à travers le pays, on a facilement réalisé que la plus grande partie du travail opérationnel dans la prévision de l'écoulement était faite par d'autres organismes fédéraux et provinciaux et les corporations hydro-électriques. Les directeurs soupçonnaient de plus que le personnel de DGEI était plus orienté vers la prévision des crues et manquait d'une appréciation équilibrée des autres besoins dans la prévision telle que pour la production de l'énergie, l'irrigation de l'aspect biologique, de la pêche et de la récréation. Les collègues américains de DGEI ont mentionné que quelques-uns des problèmes majeurs dans la prévision de l'écoulement aux Etats-Unis se trouvent dans la gestion et l'organisation.

Après une délibération plus prolongée sur le sujet, DGEI a communiqué avec les autres organismes et les corporations hydro-électriques pour voir s'ils donneraient leur appui à un atelier qui demanderait leur participation. DGEI a obtenu l'appui de ces organismes pour cette initiative et reçu des commentaires pour rendre l'atelier plus productif. Certains individus du secteur privé et du secteur académique ont aussi été recommandés pour donner à l'atelier une perspective équilibrée. DGEI est reconnaissante pour l'appui fourni par ces organismes, leurs contributions en articles techniques et en représentants, et la bonne volonté de leurs représentants d'assumer plusieurs tâches à cet atelier.

RAPPORT DU GROUPE DE TRAVAIL N^{O} 1: APPORT DE LA METEOROLOGIE

Président: W.D. Hogg
Rapporteur: D.G. Schaefer

Echange d'Information

Il y avait une discussion sur la transformation des prévisions probables du Service de l'environnement atmosphérique (SEA) aux prévisions quantitatives de précipitation. Un procédé souvent utilisé pourrait être défini par l'équation suivante:

$$QPF = AFR$$

où: QPF = la prévision quantitative de précipitation
F = un facteur discrétionnaire basé sur l'expérience météorologique
R = la pluie moyenne pour une journée où il pleut
A = une fonction d'étape

(si la probabilité de précipitation $< 50\%$, A=0)
(si la probabilité de précipitation $\geq 50\%$, A=1).

Il a été décidé que les prévisions quantitatives de la précipitation de SEA sont principalement utiles dans la prévision d'écoulement pour les avertissements des inondations et pour but d'alerte, spécialement pour les petits sous-bassins.

Il y a pression sur SEA pour concevoir les interfaces entre les données obtenues dans les prévisions synoptiques atmosphériques d'une grande étendue et les données requises pour les sous-bassins ordinairement beaucoup plus petits dans lesquels la prévision de l'écoulement est éffectuée. Il y a simplement trop de sous-bassins avec des caractéristiques très variées pour que SEA assume de telles tâches. SEA fournit et fournira le conseil aux organismes dans l'application des données de prévision synoptiques à la prévision des sous-bassins. Toutefois, la conception spécifique de l'interface pour un bassin particulier peut être le mieux réalisée par des météorologistes résidant dans le bassin et étroitement impliqués dans l'opération de la prévision de l'écoulement.

La télédétection par satellite et radar doit demeurer une responsabilité de SEA à cause des coûts associés élevés et l'application variée des données. Des méthodes pratiques, plus rapides et plus efficaces doivent être développées pour amalgamer les données de télédétection avec les données conventionnelles avant que les données par satellite et radar puissent faire une contribution significative à la prévision de l'écoulement.

Les bases de données météorologiques stables sont requises. Il devrait y avoir une communication améliorée concernant les changements de format, la discontinuation des jauges, et la relocalisation des emplacements de

radar. Des comités régionaux hydrométéorologiques formés des principaux usagers devraient se réunir périodiquement. Les comptes rendus et bulletins devraient être envoyés aux autres usagers. Quelques régions ont déjà de tels comités.

Priorités dans l'acquisition des données de prévision de l'écoulement

Les articles de données suivants sont énumérés dans l'ordre de priorité pour améliorer les prévisions de l'écoulement:

1. Température, précipitation et chute de neige spécifiées dans l'espace et le temps;

2. Le jaugeage de la pluie d'hiver requiert de l'amélioration;

3. On doit résoudre les difficultés de la mesure de la couverture de neige. Les jauges tendent à sous-attraper la pluie. Il y a maintenant assez d'information pour permettre l'ajustement adéquat des données de neige en accord avec les inclinations;

4. Radiation pour des estimés améliorés d'évapotranspiration;

5. Les déterminations de précipitation par radar requièrent des ressources considérables pour l'équipement et le traitement de données;

6. Les données de vent pour déterminer l'évaporation, la fonte de la neige, les corrections de jauge, et les embâcles.

Avec le nombre croissant de plate-formes de cueillette de données (P.F.C.D.) installées à travers le pays, des recherches devraient être effectuées afin d'établir la praticabilité de fournir les températures du sol en temps réel pour identifier le sol gelé. De plus, des méthodes pour mesurer et acquérir les données d'humidité du sol en temps réel devraient être développées. Les possibilités d'estimation de l'humidité du sol incluent les mesures de résonance magnétique, de radiation gamma, et de la télédétection par satellites.

On concède que SEA traîne de l'arrière dans l'acquisition d'autoscripteurs. Il y a des problèmes pour accomplir des enregistrements à intervalles de 30 secondes de la précipitation. Cela constitue une exigence pour la prévision de l'écoulement de très petits sous-bassins quand le temps absolu de fixation de la hauteur de pluie est important.

Jusqu'à maintenant, on a connu une faible précision dans la détermination quantitative de la précipitation par radar. L'emploi du radar semble réussir le mieux dans l'identification de la distribution spatiale de la pluie. Des applications de la technique ont réussi en Ontario. L'Alberta expérimente maintenant avec le radar. Avec de bonnes communications généralement disponibles au Canada, plus de travail doit être fait pour amalgamer les données enregistrées de la précipitation avec l'information du radar. Il y a eu des critiques à l'effet que les organismes en charge des subventions ne donnaient pas la possibilité aux universités de développer le logiciel nécessaire pour accomplir cette tâche.

Les priorités de recherche

La sensibilité des modèles d'écoulement aux données météorologiques devrait être définie. Ceci pourrait être probablement le mieux accompli en fournissant une étendue d'échelles du bassin avec des sensibilités correspondant à des paramètres spécifiques.

Il devrait y avoir un effort concerté pour fournir les limites de confiance aux données météorologiques estimées ou mesurées aussi bien que les données de pronostics.

On doit faire plus de travail pour améliorer les estimés de la couverture de neige. Les données des parcours de mesure de la neige sont souvent non-représentatives de la couverture actuelle de neige. Les valeurs extrêmes de la couverture de neige pourraient probablement être reliées à une profondeur moyenne dans un sous-bassin. Les problèmes dans l'estimation de la couverture de neige sont plus fréquents dans la région des prairies.

Les méthodes actuelles d'estimation de la diminution de neige sont généralement inadéquates. On devrait faire une revue des modèles existants de la fonte de neige avec des recommandations fournies pour l'application dans les bassins à relief topographique varié.

Des améliorations sont requises dans l'estimation des gradients de température et dans l'estimation de la précipitation avec l'élévation dans les régions montagneuses.

La conception modulaire doit être incorporée dans la modélisation afin de permettre plus de flexibilité et plus d'occasions pour réaliser des améliorations. Les modèles et les sous-routines doivent être sensibles physiquement afin de susciter l'intérêt de plusieurs usagers relativement à leur manipulation et leur fiabilité.

Les méthodes les plus efficaces et les plus fiables pour la transmission des données à partir des plate-formes de cueillette des données devraient être déterminées. Présentement, un grand nombre de données est perdu dans la transmission. La technique d'éclatement d'un météor (propagation d'une onde réfléchie d'une piste ionisée dans l'atmosphère supérieure créée par les météors) semble avoir le meilleur potentiel dans le Grand Nord. La perte des données avec le système de satellite U.S. GOES existant se produit surtout au sol entre l'île de Wallops et l'usager. Les récepteurs à Downsview et à d'autres sites canadiens pourraient améliorer remarquablement la situation quant à la réception des données de la P.F.C.D. de GOES. Une autre alternative est l'usage de MSAT, le système canadien de satellite projeté. Toutefois, GOES existe et fonctionne réellement. Il est difficile de prédire le rendement d'un système qui n'existe pas encore.

RAPPORT DU GROUPE DE TRAVAIL N° 2
APPORT DE L'HYDROMETRIE

Président: S.K. Gupta
Rapporteur: D.R. Kimmett

Systèmes en temps réel

Le comité a essayé de déterminer quel niveau de service sera probablement requis dans le futur et le niveau de service que la Direction générale des eaux intérieures (DGEI) d'Environnement Canada est prête à fournir.

Problèmes courants dans l'application des systèmes en temps réels

- La technologie du matériel change rapidement.

- Le nombre croissant de genres de plate-formes de cueillette de données (P.F.C.D.) crée des problèmes dans l'acquisition et la distribution des données.

- Les différentes P.F.C.D. et le matériel combinés avec une variété de dispositions créent des problèmes de gestion et d'entraînement.

- Il y a des besoins différents, une base de connaissance et des niveaux d'intérêt dans différentes parties du pays.

  Plusieurs organismes s'attendent à avoir besoin prochainement de plusieurs détecteurs attachés aux P.F.C.D. de DGEI.

- Des conflits de priorité apparaissent entre les usagers de données en temps réel et les organismes de gestion.

- Il y a une difficulté à amalgamer les données de l'ancienne technologie, telle que télémarques, avec les données de la nouvelle technologie.

- Il y a un besoin de centraliser l'acquisition et la dissémination des données au niveau régional.

L'état courant des p.f.c. et leurs issues

- DGEI a maintenant 95 P.F.C.D. Il y a un total d'environ 350 P.F.C.D. au Canada.

- Terre-Neuve vient de commencer un réseau en temps réel et devrait aviser le comité de coordination Canada/Terre-Neuve de ses besoins en P.F.C.D.

- La plus récente version de P.F.C.D. fournit une grande variété de détecteurs hydrologiques et météorologiques.

- DGEI, pour des raisons hydrométriques, vient de développer une norme standard pour les P.F.C.D. utilisées au Canada.

- Un seul organisme pour chaque P.F.C.D. inscrite avec le *National Environmental Satellite and Data Information Service* (NESDIS) est responsable de l'entretien des largeurs des bandes assignées de transmetteur de radio et les périodes de temps de transmission aussi bien que le contrôle d'accès des données en comparaison de l'usage de l'équipement de ligne régulière de terre dans lequel l'accès est illimité.

- Jusqu'à trois usagers secondaires peuvent avoir accès aux données de P.F.C.D. par l'emploi des codes d'identification formelle.

- Quand un système tombe en panne, les usagers demandent souvent une réparation immédiate qui n'est peut-être pas possible ou même nécessaire.

Echange d'information et questions sur les systèmes en temps réel

- La méthode courante d'accès manuel aux données en temps réel des P.F.C.D. n'est pas efficace.

- Si cette méthode était rentable, plusieurs organismes préfèreraient une acquisition centralisée de données, probablement au niveau régional.

- On a demandé aux Relevés techniques hydrométriques du Canada d'ajouter les collections de données orientées vers des tâches à son rôle historique de la cueillette de données inventaires.

- Il y a un besoin de standardisation d'équipement et de disposition de données.

- Les problèmes et contraintes de ressources humaines et de coût peuvent être résolus par la récupération de dépenses.

- Quelques organismes veulent que DGEI s'engage à montrer le chemin dans l'établissement des réseaux en temps réel.

- Comment DGEI et SEA vont-ils cueillir et distribuer les données?

- Comment DGEI s'occupera-t-elle des demandes de détecteurs spéciaux?

- La gestion des données (emmagasinage, communication, codage) requiert un développement considérable pour rencontrer les besoins courants.

- Le Ministère des ressources naturelles de l'Ontario aimerait discuter avec Relevés techniques hydrométriques du Canada de la récupération des données et du maniement des lignes de terre de transmission de données.

- Si Relevés techniques hydrométriques du Canada gérait l'acquisition de données de P.F.C.D., beaucoup des problèmes éprouvés avec NESDIS seraient réduits ou éliminés.

- Le Ministère des ressources naturelles de l'Ontario, La Direction des ressources en eau du Manitoba, et l'Hydro-Manitoba ont déchiffré les signaux audibles Telemark en utilisant les micro-ordinateurs.

Recommandations:

1. DGEI devrait travailler à clarifier et à standardiser le niveau de service qu'elle veut fournir par des énoncés politiques comme suite à la politique énoncée en 1983 par Environnement Canada sur la communication et les archives de données à partir de stations automatiques.

2. Il devrait y avoir un développement commun des directives locales d'opération et l'identification des coûts associés au niveau et au genre de service.

3. On devrait développer des programmes d'acquisition et de dissémination des données sur une base régionale.

4. On devrait considérer l'équipement automatique d'accès aux données pour obtenir l'information numérique des stations de Telemark.

Sources d'erreurs

Les courbes de niveau/débit:

Le pronostiqueur n'a pas d'autre choix que d'utiliser la relation de niveau/débit durant les crues même si elle n'est pas valide. Les conditions durant la crue causent souvent des déviations à la relation niveau/débit. Les organismes de prévision des crues et DGEI devraient se réunir au moins une fois par année avant la débâcle pour identifier les priorités et pour développer des plans conjoints réalisables. DGEI devrait aussi fournir l'information qualitative aux organismes de prévision sur les effets de remous des eaux créés par les conditions extraordinaires telles que les embâcles et les glissements de rives. D'autres conditions extraordinaires touchant les débits et niveaux telles que les déviations naturelles d'eaux et la démolition des barrages de castor, devraient aussi être mentionnées.

Les observations manuelles incluses dans les relevés historiques:

On reconnaît que les observations manuelles qui prédominaient avant 1960 peuvent influencer les analyses statistiques. Toutefois, la plupart des jauges avant 1960 étaient sur les grands sous-bassins où la définition de la réponse par une observation par jour est souvent suffisante. S'ils s'inquiètent des observations manuelles, les usagers devraient obtenir des copies

des notes de lecteur de jauge pour la révision. Les usagers devraient toujours vérifier s'ils ont une copie mise-à-jour de données que ce soit sur un ruban magnétique, sur microfiche, ou sur papier.

Débits dérivés des turbines et les courbes de tarage de déversoirs:

Ces courbes de tarage de déversoirs sont affectées par le bois et les racines à la dérive. Les débits calculés de la production des turbines ont tendance à être moins fiables que ceux évalués par les méthodes standard de jaugeage.

L'Hydro-Ontario a une routine annuelle de programme pour vérifier l'équipement et l'étalonnage. L'Hydro-Nouveau-Brunswick est en train d'ajuster ses coefficients d'étalonnage de déversoir de façon à ce que les débits calculés se conforment aux mesures de Relevés hydrométriques du Canada.

Symboles:

Les symboles B, E et A à côté des données semblent être ignorés par la plupart des usagers. Ces symboles pourraient être plus utiles s'ils pouvaient être reliés à un degré d'incertitude. On a recommandé que Relevés hydrométriques du Canada tente de fournir des limites de confiance avec ces données.

RAPPORT DU GROUPE DE TRAVAIL N^{O} 3: MODALITES DE CALCUL

Président: M.C. Quick
Rapporteur: R.D. Hofer

Problèmes dans la définition de la précision et de la praticabilité

Les membres du groupe de travail hésitaient à définir la précision des différents modèles de prévision auxquels ils étaient habitués. Cette hésitation était due au fait que la précision des pronostics dépend beaucoup de la précision et la praticabilité des données d'entrée qui sont aussi difficiles à définir et varient grandement avec le temps et l'espace. Au Canada, plusieurs modèles projetés ou présentement en usage ont été beaucoup critiqués, mais on s'accordait pour reconnaître que les prévisions sont valables et qu'une structure modèle est requise pour intégrer les ensembles de données pour réaliser les analyses de prévision des sous-bassins, des chenaux et des systèmes d'emmagasinage.

Les membres étaient préoccupés par la question des données d'entrée, en particulier: la qualité, la justesse ou l'assortiment des données aux modèles utilisés, la continuité et la distribution en temps. Les procédés d'estimation incorporés dans la conception d'un modèle devraient être appropriés aux ensembles de données disponibles pour la prévision en temps réel. Durant la période actuelle de progrès rapides dans l'informatique, les données en temps réel sont obtenues pour beaucoup plus de paramètres ou peuvent être obtenues à un coût abordable pour certaines opérations de prévision.

Classification des modèles

Les membres étaient d'accord pour que les modèles utilisés par leurs organismes soient classifiés dans quatre catégories: statistique, laminage, sous-bassin conceptuel et des combinaisons des trois catégories précédentes.

Statistique:

Beaucoup de modèles de statistiques sont en usage pour la prévision saisonnière à partir de prévisions à court terme jusqu'aux prévisions à long terme. Ceux-ci sont surtout utilisés quand la fonte de neige est le facteur principal de l'écoulement. La plupart se servent d'une certaine forme d'état d'humidité du sol antécédente du sous-bassin.

Quelques prévisions saisonnières sont basées seulement sur l'humidité antécédente et la précipitation, et débit d'étiage.

Les modèles de statistiques dépendent d'un long relevé de données mesuré d'une manière semblable au même endroit pendant de

nombreuses années. Les modèles de statistiques sont définis par les ensembles de données en série de temps historique à des endroits prescrits et sont par conséquent limités dans leurs

applications à ces endroits et ces ensembles de données prédéfinis. Par comparaison, un modèle conceptuel peut être adapté pour utiliser de nouvelles données à mesure qu'elles deviennent disponibles, et de tels modèles peuvent être utilisés pour engendrer des prévisions saisonnières.

Quelques usagers ont affirmé avoir obtenu de bons résultats à partir des méthodes de statistiques pour les prévisions à court terme.

Plusieurs usagers ont rapporté que ces modèles de statistiques de prévisions saisonnières ont un penchant pour la moyenne à long terme. Toutefois, même un modèle conceptuel utilisé pour les prévisions saisonnières doit avoir recours à la climatologie après un horizon à temps court d'environ 5 jours résultant en prévisions se rapprochant de la moyenne à mesure que le temps d'horizon est prolongé.

Les modèles de statistiques ont été utilisés pour prévoir le volume et la crue. Cependant, les prévisions tendent à être beaucoup plus fiables que les prévisions de crue.

Sous-bassin conceptuel:

Beaucoup de modèles conceptuels ont trop de paramètres et les procédés sont vagues. Quelques usagers ont remarqué qu'un rendement semblable de modèle peut être obtenu avec différents ensembles de valeurs de paramètres. Ceci démontre la nature non physique de quelques paramètres.

La plupart de modèles ont une structure intra-reliée tellement complexe que les procédés individuels ne peuvent pas être aisément séparés. Si les procédés pouvaient être séparés, il serait possible de tester les composants de modèles et même de substituer de nouvelles méthodes pour modeler les composants individuels. Par conséquent, la conception modulaire devrait être employée de telle façon que les modèles puissent être adaptés à de nouvelles techniques et de nouvelles entrées de données.

On a exprimé un besoin pour la capacité interactive dans les modèles. Cette capacité aiderait les usagers dans l'exploration de la sensibilité des paramètres aussi bien que dans la promptitude du calibrage.

Laminage:

La plupart du laminage est présentement accompli par les modèles de types hydrologiques dans lesquels les paramètres d'emmagasinage et de remous des eaux sont ajustés à des évènements observés dans le passé. Les modèles tels que SSARR, SIMPAK et Muskingum utilisent ces méthodes. Quand il y a des conditions compliquées de remous des eaux, les réseaux hydrauliques complexes ou les conditions de borne de marée, les modèles hydrodynamiques sont utilisés. Ces modèles utilisent les données topographiques de chenaux, et requièrent un effort de traitement de données

plusieurs fois plus grand que celui des modèles de type hydrologique. Les membres du groupe de travail ne réalisaient pas qu'il y avait un usage opérationel au Canada d'un groupe intermédiaire de modèles connu dans la littérature comme les modèles d'onde cinématique et d'onde de diffusion. Les modèles existants de laminage semblent être complètement adéquats étant donné les problèmes existants dans la modélisation des sous-bassins qui donne l'entrée aux modèles de laminage.

Nouvelles méthodes et approches

Une technologie de communication progressant rapidement rend plus de données facilement accessibles dans un temps court pour un plus grand nombre de paramètres à un coût moins élevé. Cette technologie rend possible l'incorporation de nouvelles routines ou composantes dans les modèles conceptuels. Le besoin le plus grand dans ces routines est probablement la mise à jour rapide et fréquente. Le groupe de travail avertit aussi que des méthodes efficaces doivent être incorporées avec l'acquisition des données pour accomplir les tests de vérification et de fiabilité des données. On s'attend à ce que beaucoup de ces données fréquemment obtenues proviennent des P.F.C.D.

De nouvelles sources de données telles que les images de satellite et les estimés de précipitation par radar devraient être disponibles sur une base fréquente en temps réel. Les rélevés aériens de neige par rayons gamma deviendront plus réalisables pour une utilisation sur une base peu fréquente. Cette information devra être incorporée dans la structure du modèle et mélangée avec les autres données d'entrée. Une recherche plus poussée à l'appui de l'étude de ce procédé d'amalgamation est une question qui revêt de l'importance.

Dans beaucoup de cas, un modèle de régularisation est nécessaire pour la prévision. Un modèle de sous-bassin avec un algorithme simple de laminage est inadéquat pour un système fortement régularisé de chenaux et de réservoirs. Il y a une tendance à incorporer les techniques de la recherche opérationnelle (optimalisation) aux modèles de régularisation. Ces techniques permettent une opération décentralisée mais en même temps intégrée du bassin (approche holistique).

Les besoins de recherche

La nature non-physique de beaucoup de paramètres de modèle et leur relation inquiètent les usagers. On a besoin d'une recherche plus avancée pour définir les procédés variés impliqués dans le comportement des sous-bassins. Les procédés suivants sont spécialement identifiés comme étant d'une importance particulière:

> Plus de recherche a été recommandée sur la fonte de neige qui est encore calculée surtout par l'approche de degré-jour. On a rapporté qu'une approche de budget d'énergie était plus précise pour les petits sous-bassins équipés d'instruments de test, mais en ce qui concerne les sous-bassins, spécialement ceux d'une étendue de plus de 100 km^2, la méthode de dégré-jour s'est révélée être légèrement supérieure.

L'humidité du sol présente plusieurs problèmes tels que: la détermination des conditions antécédentes, l'influence du gel du sol et l'infiltration d'eau. Le gel du sol a été identifié comme un problème majeur pour la modélisation de l'écoulement sur les prairies avec une basse couverture de neige. On a affirmé que l'écoulement combiné de la fonte de neige et de la pluie pouvait varier de 10 % à 90 %, dépendant de l'étendue du gel sur le sol et du taux de fonte de neige.

Dans son article à cet atelier, M. Morton, mentionne plusieurs cas de recherche sur l'humidité de sol, l'évaporation et l'eau souterraine.

On a besoin de plus d'ouvrage pour définir le bilan thermique et la maturité de la couverture de neige de façon à prévoir plus sûrement le début de l'écoulement provenant de la couverture de la neige. La prévision de la crue pour les prairies ainsi que pour les régions montagneuses est très sensible à la prévision du début de la fonte de la couverture de neige.

On doit mettre à l'essai les modèles conceptuels de sous-bassins en se servant des données de bonne qualité provenant de sous-bassins bien équipés d'instruments. On pense que c'est la seule façon dans laquelle un progrès efficace peut être fait pour améliorer la conception et la fiabilité des modèles. Le rapport des estimations du rendement économique des modèles dont les nouvelles caractéristiques ont été développées lors d'une mise à l'essai contrôlée est de l'ordre de 20 à 1 et 10 à 1. Ce bon rendement économique pour les organismes dans la production des prévisions plus précises justifie la réactivation des bassins de recherche de la DHI (Décennie hydrologique internationale). Beaucoup des données de DHI n'ont jamais été utilisées et peu d'entre elles ont été préparées pour le traitement électronique de données. Une étude préliminaire est recommandée pour déterminer la possibilité d'utiliser ces données.

RAPPORT DU COMITE DE TRAVAIL N^{O} 4
GESTION ET ORGANISATION

Président: J. G. Lockhart
Rapporteur: J. Robinson

1. Cadre institutionnel et organisation

- Les structures d'organisation des centres de prévision des crues du Nouveau-Brunswick, du Manitoba, et d'Ontario ont été révisées.

- Puisque l'eau est une ressource provinciale, conformément à la Constitution, la responsabilité pour la prévision des crues devrait donc appartenir aux provinces. Cependant, la responsabilité pour la prévision des crues n'est pas réellement bien définie dans certains cas tels que pour les rivières internationales et interprovinciales.

- Chaque structure d'organisation doit être unique pour s'adresser aux circonstances et besoins régionaux. Une histoire, un milieu économique et social différents nécessitent une structure d'organisation particulière.

- On était d'accord généralement qu'il y a certains avantages à ce qu'une structure de comité fournisse l'expertise, les données, l'appui technique et la communication. Certains participants ont suggéré que le *U.S. National Weather System (NWS)* est plus efficace qu'Environnement Canada en fournissant les services aux unités de prévision des crues. On a remarqué que NWS a la responsabilité des prévisions de température aussi bien que la prévision des crues. Ces participants ont de plus suggéré que l'efficacité pourrait être améliorée en amalgamant SEA et DGEI.

- La participation du gouvernement fédéral est avantageuse dans l'établissement des centres de prévision de l'écoulement, mais devrait être retirée quand les centres deviennent complètement opérationnels.

- On ne recommande aucun changement dans l'organisation et les responsabilités existantes. Cependant, il y a certains endroits (la Colombie-Britanique et le Québec) où la responsabilité pour la prévision de l'écoulement n'est pas bien définie à cause de l'exploitation des réservoirs par les compagnies hydro-électriques et la surveillance par un organisme du gouvernement provincial.

- Il devrait y avoir des agences de direction régionale ou provinciale dont le mandat serait de fournir les prévisions de l'écoulement.

2. Personnel

Chaque agence a révisé sa situation particulière relative au personnel et les points suivants ont été soulignés:

- La composition du personnel des organismes étudiés a été jugée minimale pour fournir les prévisions précises et à jour des crues et des niveaux.

- Ce personnel est insuffisant pour soutenir une opération à l'année longue.

- L'entraînement fréquent du personnel et la valorisation de l'expertise sont essentiels. On a suggéré que le cours l'Introduction aux principes hydrologiques soit rétabli par le sous-comité sur l'hydrologie du Conseil National des Recherches.

- La réduction du personnel est en certains cas compensée par l'automatisation suite au progrès de l'informatique.

- Une bonne documentation des méthodes et procédés de prévision est nécessaire pour maintenir la continuité des prévisions durant un changement de personnel ou lors de longues absences de celui-ci.

3. Communications

Les méthodes et techniques suivantes ont été révisées: P.F.C.D., télécopieur, téléphone, les circuits de SEA, téléphone à code, radar, unité d'appels automatiques, réseaux commutés de transmission de données par paquets tels que DATAPAC et INFODAT, les terminaux d'ordinateur, et micro-ordinateurs pour accéder aux unités centrales de traitement à l'aide de points d'accès par téléphone pour l'acquisition automatique de données et le courrier électronique (projet pilote sous révision par le ministère des ressources naturelles de l'Ontario).

On a mentionné que SEA peut transmettre de grandes quantités de données hydrométéorologiques et climatologiques par des circuits réservés de communication. Ceci peut être plus efficace que les procédés couramment utilisés pour le coût. On doit se servir plus efficacement des cartes de risque d'inondation, des banques, des courtiers en immeubles, et des compagnies d'assurance en soulignant au public et aux fonctionnaires municipaux le besoin et la valeur de la prévision de l'écoulement.

Echange de communication:

Dans le moment il y a peu d'échanges entre les centres de prévision de l'écoulement. Cette réunion a fourni aux représentants des centres de prévision la première occasion de se rencontrer et de discuter de leurs opérations.

Le comité de travail était d'accord pour qu'il y ait une réunion annuelle ou semi-annuelle des représentants des centres de prévision. Il n'est pas nécessaire que la disposition de ces réunions ait un caractère officiel.

La Centre de prévision de la rivière St-Jean a offert de coordonner et d'être l'hôte pour une telle réunion à Frédéricton. La date suggérée du 14 au 16 novembre 1984 a été choisie pour coincider avec une réunion du Comité de travail sur les ressources en eau du Comité canadien consultatif sur la télédétection.

4. La cueillette de données

SEA, Relevés techniques hydrométriques du Canada, les agences provinciales et les compagnies hydro-électriques font couramment la cueillette des données. Les types de données sont généralement climatologiques, météorologiques, hydrométriques et de prévision.

Il y a un besoin pour les données suffisantes en temps réel pour assurer la fiabilité des prévisions.

Dans la révision de l'imagerie par satellite il a été convenu que ces données sont utiles dans la définition de l'étendue de la couverture de neige. "Unifax" est un outil utile pour fournir aux centres de prévision l'information sur les conditions atmosphériques provenant des satellites. Le Manitoba a exprimé un besoin pour les prévisions objectives sur la précipitation quantitative de SEA qui peuvent être modifiées subjectivement par les usagers, s'il est nécessaire. Ce genre de données serait plus utile que les probabilités de prévisions de précipitation qui doivent être transformées subjectivement en valeurs quantitatives par l'usager.

L'échantillonnage de la neige par des rayons gamma est actuellement évalué pour fournir les équivalents neige/eau. Cette technique peut avoir des applications définies dans certaines régions, toutefois l'efficacité économique est douteuse.

Il y a un besoin pour les données par radar au Nouveau-Brunswick et en Colombie-Britanique. Certains participants à l'atelier ont démontré que l'aspect pratique du radar dans les terrains montagneux, tel qu'en Colombie-Britanique, demeure aléatoire.

5. Production des prévisions

La fréquence utile des prévisions dépend des niveaux actuels de crues ou du danger anticipé d'inondation. Les compagnies hydro-électriques requièrent généralement des prévisions journalières durant les périodes de crues.

Jusqu'à maintenant, au Canada, les probabilités sont incluses dans les prévisions pour seulement les prévisions de moyen à long terme au Manitoba et pour les Grands Lacs.

6. Dissémination des prévisions

Les résultats des prévisions de crue sont fournis aux agences du gouvernement, aux compagnies hydro-électriques et au public par les moyens suivants:

- communiqués de presse;
- télécopies aux agences de gestion et du gouvernement;
- les messages téléphoniques codés (mis à jour comme requis par la situation);
- accès à distance par terminal aux prévisions emmagasinées dans les unités centrales de traitement;
- l'Organisation des mesures d'urgence alerte les municipalités du besoin de certaines mesures basées sur l'interprétation des prévisions de crues pour des régions spécifiques;
- les Autorités de conservation de l'Ontario fournissent la plus grande partie de la communication avec les municipalités qui à leur tour communiquent avec le public local et les média.

Alerter ou aviser d'une inondation est préférable à taire l'information de prévision ou au «silence» à cause d'une incertitude. Toutefois, on doit être prudent de ne pas trop réagir et détruire la crédibilité des prévisions. Le comité de travail a discuté de la disponibilité de techniques de prévision à coût réduit pour les petits cours d'eau avec les débits très variables pour lesquels aucune prévision n'est actuellement faite. On a mentionné que le «U.S National Weather Service» et d'autres organismes étrangers ont développé des techniques simplifiées pour fournir quelques systèmes utiles d'alerte d'inondation.

On reconnait que, fréquemment, des problèmes de juridiction se produisent relativement aux émissions de prévisions à des endroits spécifiques.

7. Budget et finances

Le comité de travail a révisé les accords actuels de partage des coûts au Nouveau-Brunswick et au Manitoba.

De façon à justifier les coûts de prévision de l'écoulement, il est nécessaire de connaître les dommages causés par les inondations et associés à celles-ci par la fréquence de leur manifestation.

Les méthodes utilisées actuellement semblent très imprécises. On devrait développer un système standardisé pour identifier et estimer les coûts des dommages d'inondation.

Les ressources appliquées à l'effort de prévision devraient être reliées aux bénéfices attendus. Les procédés coût/bénéfice devraient être développés pour justifier le coût d'amélioration des prévisions de l'écoulement pour un bassin particulier.

Sommaire comparatif d'organisation

Le président de l'atelier a présenté le sommaire d'organisation comparatif suivant pour les 12 organismes de prévisions de l'écoulement représentés à l'atelier.

	nombre d'organismes
1. Organisation	
- centres relativement séparés	4
- bureaux régionaux	2
- partie intégrale de l'organisme	6
2. But des prévisions	
- usages multiples	4
- prévisions de crue	4
- prévisions hydrométriques de crue	2
- hydrométrie	2
3. Dissémination des prévisions	
- générale	8
- sur demande	2
- interne seulement	2
4. Modèle de l'écoulement	
- fait sur demande	5
- logiciel américain	4
- statistique	3
5. Laminage	
- hydraulique et/ou hydrodynamique	2
- hydrologique	7
- temps de latence simple	3

Tendances à noter

La liste suivante de tendances surgissantes dressée par le président et le secrétaire de l'atelier fut présentée:

1. Très prochainement, les prévisions météorologiques quantitatives seront prolongées des 2 jours actuels à 10 jours.

2. L'automatisation de l'acquisition de données aux moyens de P.F.C.D., d'autoscripteurs de données et d'autres appareils est poursuivie par la plupart des organismes de prévision de l'écoulement.

3. Au moins 2 organismes à l'atelier font entrer actuellement automatiquement les données météorologiques et hydrométriques dans leurs modèles. On s'attend que cette tendance continue avec les

besoins croissants pour la rédaction efficace des données et la vérification des algorithmes.

4. Les usagers demandent et obtiennent l'accès direct aux prévisions par des méthodes telles que téléphone à code, accès par terminal aux fichiers sur disques des unités centrales de traitement.

5. La contribution des données de radar et l'imagerie de satellite n'ont pas donné les résultats escomptés.

6. La fascination pour les mathématiques décroît pour être remplacée par une fascination pour la technologie électronique.

7. A mesure que la connaissance informatique augmente il y a une migration catégorique de modèles du genre à régression aux modèles conceptuels.

8. Il n'y a eu aucun progrès évident durant les 10 dernières années dans le dévoloppement de modèles à base vraiment physique.

9. Dans les endroits urbanisés avec les réseaux hydrauliques compliqués les remous des eaux il y a une utilisation et une demande croissantes pour le laminage hydrodynamique.

10. Il y a une tendance et une demande croissantes de joindre les probabilités aux prévisions.

11. Il y a une reconnaissance croissante de l'importance de la mise à jour fréquente et rapide des modèles conceptuels rendue possible par les avances actuelles rapides dans l'informatique.

12. La prévision de l'écoulement, comme d'autres opérations du gouvernement fédéral et des gouvernements provinciaux, subit des restrictions financières et des demandes de bénéfices nets pour un niveau approprié de service.

RECOMMANDATIONS

Le président de l'atelier a présenté des recommandations qui ont été révisées par tous les participants. Les recommandations étaient les suivantes:

1. Il y a un besoin pour un échange continu d'information entre les centres de prévisions de l'écoulement (Le centre de prévision de la rivière St-Jean a offert d'être l'hôte d'un atelier semblable l'année prochaine à Frédéricton).

2. Il y a un besoin pour des comités hydrométéorologiques régionaux formés des collectionneurs de données ainsi que des usagers.

3. Le sous-comité sur l'hydrologie du CNR, ou tout autre groupe professionnel, devrait considérer:

   - une révision approfondie de la vieille information de recherche et des recommandations pour les méthodes conceptuelles futures;
   - la reprise de la formation d'introduction sur les principes hydrologiques.

4. SEA devrait tenter de rendre ses produits de données plus compatibles avec les besoins de la prévision de l'écoulement en se servant de l'informatique contemporaine.

5. DGEI devrait clarifier quel niveau de service elle est prête à fournir, et devrait documenter pour chaque région les coûts des différents niveaux de service.

6. Les efforts de recherche devraient tenir compte des articles suivants:

   - recherche fondamantale sur les procédés physiques;
   - des moyens plus efficaces pour rédiger et introduire les données en temps réel;
   - des méthodes pratiques pour amalgamer les données de radar et/ou l'imagerie de satellite avec les données conventionnelles;
   - réduire la perte des données dans les techniques de cueillette automatique en considérant d'autres options telles que l'éclatement de météor, MSAT;
   - comparaison et évaluation des modèles utilisés au Canada;

7. Les développeurs de modèles devraient considérer:

   - l'approche modulaire et la capacité de transport pour accommoder les progrès de la recherche;
   - les techniques d'optimalisation pour accommoder l'exploitation des réseaux des réservoirs et chenaux;
   - le développement de la capacité d'accepter automatiquement les données en temps réel de façon à mettre à jour fréquemment et rapidement les conditions antécédentes;
   - le développement des «modèles à la portée de l'usager».

8. Les collectionneurs de données et les développeurs de modèles devraient travailler à une meilleure définition de l'erreur prévue et les limites de confiance de leurs produits.

9. L'information de prévision devrait être intégrée par les techniques reprographiques avec les cartes de risques d'inondation; toutefois cette information doit être présentée au public avec prudence.

10. Les techniques d'évaluation financière devraient être développées pour justifier économiquement les prévisions et pour définir les niveaux appropriés de service pour les besoins identifiés.

PART II

BACKGROUND AND THEME PAPERS

PARTIE II

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Meteorologic Inputs to Forecasting

The Alberta River Forecast Centre Experience

Jim Bowers

September, 1983

Alberta River Forecast Centre
Alberta Environment
Edmonton, Alberta

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Summary

The Survey Branch of the Technical Services Division of Alberta Envrionment presently operates a network of 30 automatic, telemetry equipped, meteorological stations for the River Forecast Centre (R.F.C) of Alberta Environment. 19 of these are GOES DCPs, and 11 rely upon telephone lines. We also access data from automatic meteorologic stations operated by the Alberta Forest Service, the Banff Park Administration, the Bonneville Power Administration and the U.S. Soil Conservation Service. The meteorological data from these sources is used, in conjunction with data from the more traditional human observer sources, to provide a real-time river forecast service to Alberta . A major use of the meteorological infornmation is as input data for an interactive version of the SSARR (Streamflow Synthesis And Reservoir Regulation) simulation model, developed by the U.S. Army Corps of Engineers. The R.F.C. uses the interactive SSARR model to simulate the entire South Saskatchewan headwaters and parts of the North Saskatchewan and Athabasca headwaters. The simulation model is used on a routine basis (simulations are made at least 3 times a week) for the purpose of generating flood warnings, reservoir inflow forecasts and providing river flow forecasts.

The paper discusses how the R.F.C. collects and uses the meteorologic data for its day to day forecasting operations. In particular, the importance of the meteorological data to the SSARR simulation model is discussed. The adoption of the interactive version of the SSARR model has had an impact on how the R.F.C. presently uses meteorological data, and will have a major impact on future operations. The differences between the interactive version and the standard version of the model are discussed.

The main intent of the paper is to describe the system that has developed and evolved at the R.F.C. over the past 10 years for the operational use of meteorologic data in a real-time river forecasting operation.

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Part 1 The River Forecast Centre

The River Forecast Centre is one of four branches in the Technical Services Division of Alberta's Department of the Environment. The R.F.C. 's mandate consists of four broad objectives:

- *To provide flow forecasting for flood warnings and optimum management of the water resources of the province.*
- *to advise on reservoir operations in order to provide optimum management of the water resources of the province.*
- *to ensure an adequate data collection network and data transmission system to provide the hydrometeorological data for flow forecasting.*
- *to advise on the administration of the Apportionment Agreement by the Prairie Provinces Water Board.*

To fulfill this mandate the R.F.C. must provide both long-term and short-term forecasting services, as well as provide advice on reservoir operations in the province. The R.F.C. produces water supply forecasts throughout the spring and summer and has done a large amount of work in developing reservoir operation procedures. Considerable expertise as been developed in the area of hydrologic modelling, and the R.F.C. provides consulting services in this area to other parts of the department.

The major function of the R.F.C. is what we refer to as "operational forecasting" . Operational forecasting is the day to day routine of providing short-term river flow forecasts, including flood forecasts, to the general public and a variety of public and private agencies. Originally the R.F.C. short-term forecasting operations were primarily flood oriented, but the R.F.C. has found that there is an increasing demand for general short-term flow forecasts as the demand on water resources in Alberta increase. Flood forecasting is still a major concern.

The R.F.C. uses the SSARR model to simulate most of the headwaters of the South Saskatchewan basin and parts of the North Saskatchewan and Athabasca basins. In these areas SSARR is used for routine forecasting tasks, such as reservoir inflow forecasts, as well as for flood forecasts. For other parts of the province that do not require routine forecasting, but that can experience flooding, the R.F.C. has developed special flood forecasting procedures. These flood forecasting procedures are based on unit hydrograph techniques. They are used only for flood forecasting, not for routine forecasting.

The R.F.C. presently consists of 8 full time staff involved in forecasting duties, 1 person in a temporary position who assists with data handling, and 1 secretary. During the active forecast season (April - October) operational forecasting is handled by the forecasters on duty. Duty is rotated on a weekly basis, with teams of two forecasters being on duty for each week. During the weeks they are on duty the forecasters carry pagers

and are available 24 hours a day, 7 days a week. A third forecaster is normally available to help the forecasting team with data handling, but is not considered to be on call. During a major flood or other particularly busy times the duty forecasters may call in other staff to assist them. The other staff not involved in day to day forecasting will normally be involved in water supply forecasting or other long-term projects.

Part 2 Meteorological Network

2.01 Network Development

The R.F.C. meteorologic network has been designed with specific forecasting goals in mind. In 1978 the R.F.C. proposed that the existing network of meteorologic and hydrometric stations in the headwaters of the South Saskatchewan River be expanded. The primary reason for this proposed network expansion was to provide real time data for flood forecasting in the South Saskatchewan basin. There were 6 automatic meteorological stations equipped with telemetry in operation in the South Saskatchewan headwaters at that time. The R.F.C. relied heavily upon the observer networks operated by other agencies for real-time information for forecasting. The existing observer networks consisted mainly of fire towers (lookouts) and ranger. stations operated by the Alberta Forest Service (A.F.S.), and Atmospheric Environment Service (A.E.S.) observers. A network of storage gauges is also operated by the A.F.S..

The existing observer network was inadequate for several reasons;

1. The density of the stations was not adequate.

2. The major consideration in locating the A.F.S. stations had been for the purposes of forest fire observation and forestry administration. This meant that the stations were not

normally located in areas that were representative of the watersheds.

3. The major consideration in locating the A.E.S. observers had been the availability of year round observers. This meant that the mountainous headwaters areas of the South Saskatchewan River were left relatively ungauged.

4. The frequency of the reports from the stations was low, most of the observers made only 1 or 2 observations per day.

29 new remote automatic telemtered meteorologic stations were proposed to supplement the existing networks and rectify some of these problems.

In 1980 the R.F.C. proposed some modifications to the South Saskatchewan network to support the forecasting requirements of the Dickson Dam. The Dickson Dam was to be constructed on the Red Deer River upstream of Red Deer. Construction began in 1981, and the structure first began to store water in the spring of 1983. The primary function of the Dickson Dam is to provide asssured winter water supply to support industrial expansion in the Red Deer area. The dam also provides flood control and recreational benefits. The R.F.C. developed the operational strategy for the project.

7 more automatic meteorologic stations, beyond those recommended in the South Saskatchewan proposal, were recommended. The schedule for installation was also altered so that the

network in the Red Deer headwaters would be completed by the time that construction on the dam was underway.

In 1981 the R.F.C. proposed a network to support the flood control dam which was to be constructed on the Paddle River, a tributary of the Athabasca River. The R.F.C. developed the operational strategy for this project. Accurate flow forecasting was a crucial part of the proposed strategy and will help to maximize the flood control capabilities of the project. The proposed network included 6 remote meteorolocial stations equipped with telemetry. The Paddle Dam will begin operations in the spring of 1984.

All three proposals also included proposals for hydrometric stations equipped with telemetry to be installed, as well as the meteorologic stations. Although there have been some changes from the original proposals, the networks are all being implemented. By 1985 all three networks should be completed. The R.F.C. will then be operating with a network consisting of 48 automatic meteorologic stations equipped with telemetry. Map 1 is a map showing the locations of the automatic stations in the R.F.C. South Saskatchewan network, and Map 2 shows the location of the stations in the Paddle network.

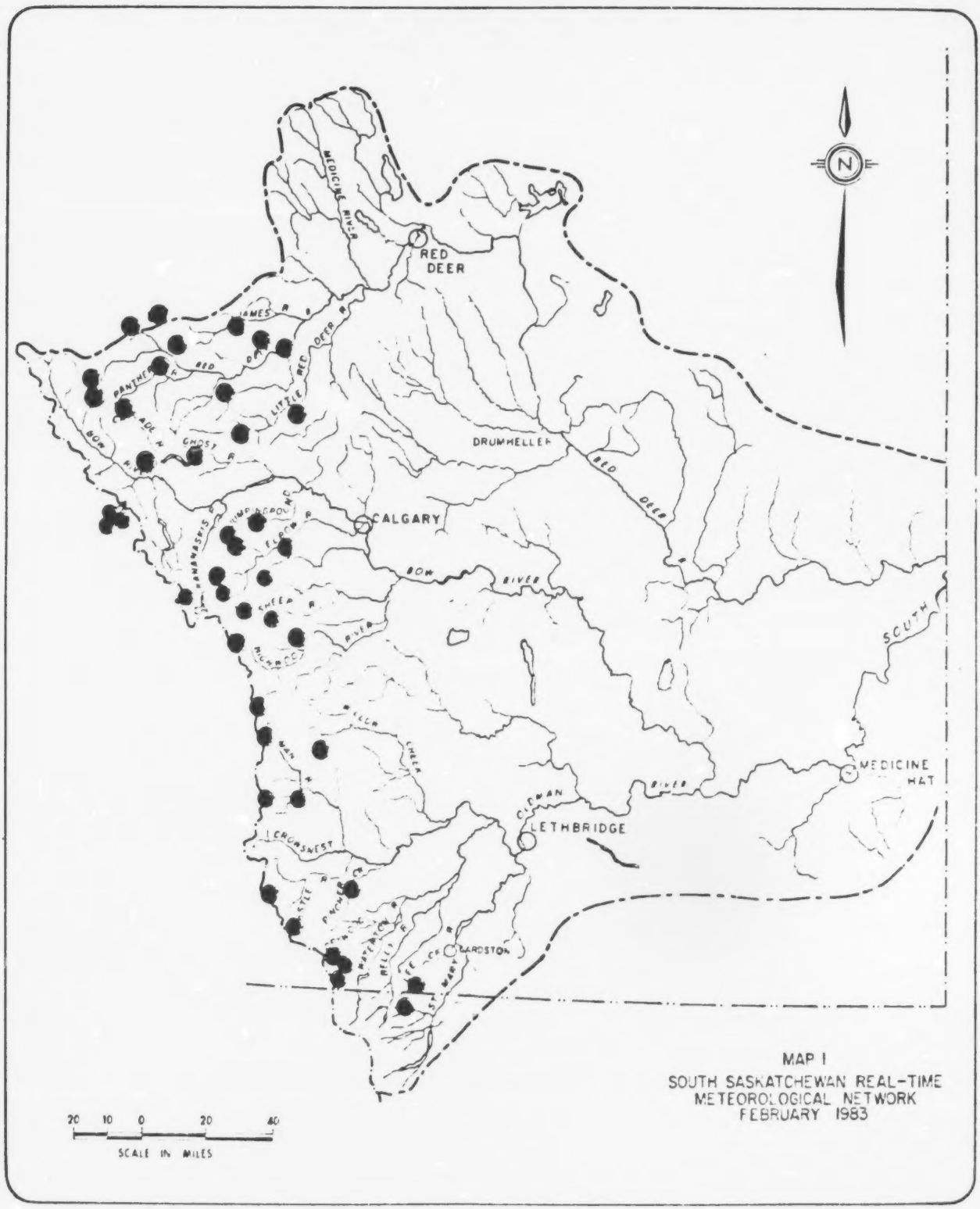
In all three proposals a major concern was to make sure that the meteorologic data from these remote stations would support the use of a streamflow simulation model. In the operational strategies of both the Paddle River and Dickson Dams streamflow forecasting is a critical part of their operations, particularly

in their role as flood control structures. The original South Saskatchewan network was proposed primarily so that the R.F.C. would have real-time data to support streamflow forecasting in that area. The meteorologic station locations were selected with these requirements as the primary concern. The result of these proposals is that the R.F.C. now operates a network of remote telemetered meteorological stations that has been primarily designed to provide real-time meteorologic data for a streamflow simulation model. These stations should also provide good data for the purposes of water supply forecasting because representative locations have been selected. The period of record for the stations is too short at present to use the data for water supply forecasting.

While the role of the other existing networks in the R.F.C. operations has been greatly reduced with the near completion of the R.F.C. network, the other networks still remain important.

Information from the SNOTEL system, operated by the United States's Soil Conservation Service (U.S.S.C.S.), and the GOES DCP's operated by the Bonneville Power Administration (B.P.A.)is the only real-time meteorologic information that we receive from those parts of the headwaters of the St. Mary River that lie in Montana. The St. Mary River is an important source of irrigation water for Alberta, and an important tributary to the South Saskatchewan River. The R.F.C. is working on the installation of two automatic stations equipped with GOES telemetry in northern Montana.

The R.F.C.'s flood forecasting responsibilities cover all of Alberta, not just the South Saskatchewan and Paddle River basins. For some areas of Alberta the A.F.S. and A.E.S. observer networks are the only real-time sources of meteorologic information to use for flood forecasting. Where the older networks and the R.F.C. network overlap, we are able to take advantage of the greater density to produce more accurate estimates of mean watershed precipitation.



MAP 1
SOUTH SASKATCHEWAN REAL-TIME
METEOROLOGICAL NETWORK
FEBRUARY 1983

Paddle River Basin

REAL-TIME METEOROLOGICAL NETWORK

(00) Active Stations

February, 1983

Map 2

2.02 Telemetry and Instrumentation of the R.F.C. Network

2.03 Instrumentation

The R.F.C. operates two basic types of automatic meteorologic station:

1. Full climate stations

2. Precipitation and temperature (P+T) stations

Full climate stations are equipped with all of the following types of sensors, the P+T stations are only equipped with a precipitation gauge and temperature sensor.

- Precipitation.

  The standard automatic precipitation gauge is the Fischer Porter gauge (now made by Belfort). In cooperation with A.E.S. in Edmonton, the following interface method was developed. A Baldwin (model 5V86-CGX-1) absolute position encoder was mounted on the gauge to mesh with the gear on the back of the dial gauge. The encoder has a paralell BCD gated output with a count range of 0 to 999 per revolution, this provides ouput to the nearest one hundredth of an inch. The telemetry is completely independent of the punch tape mechanism of the gauge, so each system can serve as a back up for the other. The telemetry does not affect the normal operation of the Fischer Porter in any way. The encoder has proved very

reliable. Four of the original encoders have been operating continuously since 1977, with no problems. The limited capacity of the Fischer Porter gauge (490 mm) means that fairly frequent service trips are required to prevent over topping. The telemetry allows us to monitor the gauges so that service trips can be scheduled only when they are required.

- Temperature.

  The sensor used to measure temperature for those stations using telephone telemetry is the Sonotek MITS Micropower Temperature Sensor. The temperature shield used is the A.E.S. designed paralell plate shield. A Y.S.I. Thermistor is used for those stations using GOES satellite telemetry. No problems have been encountered with either temperature sensor.

- Humidity.

  The standard sensor used to measure humidity is the Pernix Type 800w L100 Sensor. They appear to be giving good service. The R.F.C. has not carried out systematic checks on these humidity sensors in the field.

- Wind Speed and Direction.

  The Sonotek 77c aneometer has been adopted as the standard wind sensor. These instruments are expensive, and present some interfacing problems with some of the data collection platforms (DCP's) use for GOES satellite telemetry.

- Snow.

  A 3 metre diameter snowpillow, filled with a solution of methyl alcohol is used to measure snow pack water equivalent. The solution in the pillow is connected directly to a stilling well. The level in the well varies in direct porportion to the pressure of the snow on the pillow. A Leupold and Stevens water level recorder is used to measure the level of the liquid in the well. The water level recorder is interfaced with the telemetry using a Baldwin encoder. The system for telemetering snowpillow data has been very reliable. The snowpillow itself has some drawbacks as a means for measuring snow water equivalent, particularly during the crucial melting period. The R.F.C. is investigating nuclear snow gauges as an alternative.

- Radiation

  Although no radiation data are being collected at present, equipment is being purchased to measure incoming and outgoing radiation at two of the sites. The sensors will be made by LI-COR (model number L-1 -200-SB). It is hoped that radiation data will aid in the simulation of the snow melt process.

Maintaining the automatic meteorologic stations themselves is the responsibility of the Water Survey Section of Alberta Environment. The Water Survey Section also has done most of the installation work and assisted in the final

phases of the meteorologic site selection process. The forecasting team is responsible for reporting any meteorologic station problems to the Water Survey Section. The forecasting team is also responsible for monitoring the various telemetry systems that are used to collect the data and reporting any transmission problems to the appropriate agency.

2.04 Telemetry

1. Data Telemetered by Telephone Lines

Telephone telemetry is the major system used by the R.F.C. for collecting hydrometric data, TELEMARKS being the main type of telemetry. Several of the R.F.C.'s automatic meteorological stations also use telephone telemetry. These stations are referred to as DATEK stations. DATEK is the name of the company that developed the hardware that is used. The DATEK unit consist of a small microprocessor which responds to a telephone call by interogating the meteorological sensors and then transmitting a signal containing the information. Unlike a TELEMARK, this is not an audio signal which can be understood by human ears, a computer terminal is required to receive the transmission. Several hydrometric stations have also been equipped with DATEK units.

2. GOES Telemetry

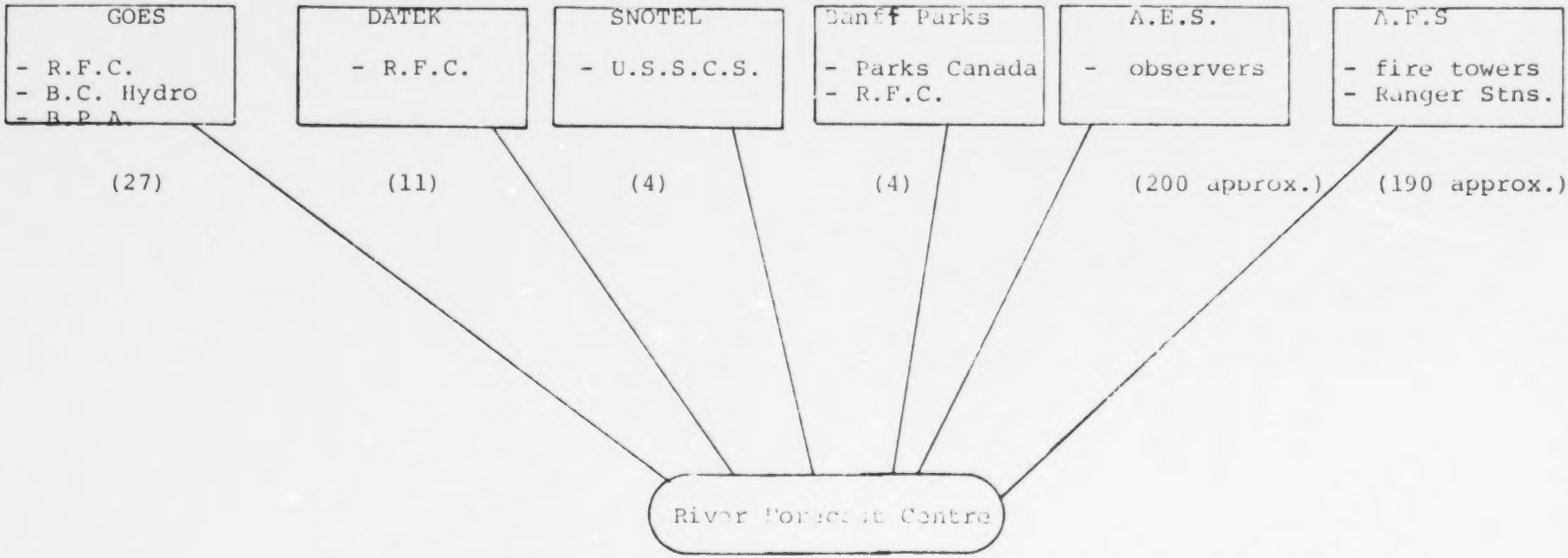
The majority of the automatic meteorological stations operated by the R.F.C. use GOES satellite telemetry. GOES telemetry was selected because of the remote locations of many of the sites. Data is transmitted from the site to the GOES satellite, which is in a stationary orbit over the equator. The satellite then transmits to a ground station at Wallops Island, Virginia, from there the data is transmitted to the National Environmental Satellite Service (NESS) computers in Maryland. We have found the system extremely reliable, with a very high success rate for data transmissions. Data reception from the GOES stations is more reliable then from those stations that use telephone telemetry. Telephone lines can be affected by bad weather, such as usually accompanies floods, and this has been a problem in the past. The R.F.C. uses GOES data collection platforms manufactured by both Handar and Bristol Aerospace.

Part 3 Operational use of Meteorologic Data

3.01 Data Handling

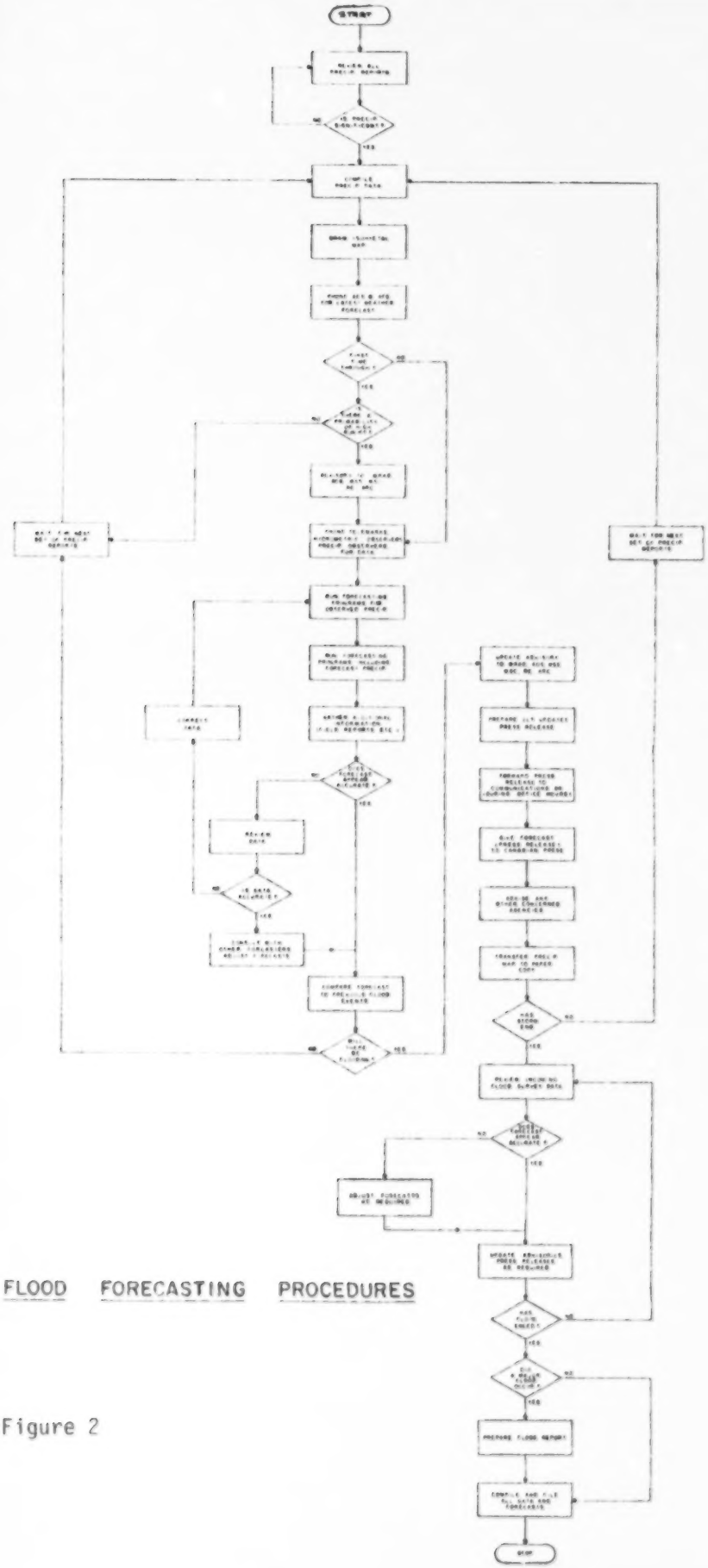
The flowchart (*figure 1*) illustrates the flow of meteorological data into the R.F.C. . Once the data is received by the R.F.C. it must be decoded, checked, and archived. The following is a brief summary of the meteorological data handling process, broken down by the sources of the data. If the data indicates potential flooding the forecasting team begins to go through the flood forecasting procedure, illustrated in *figure 2*, otherwise the data handling process is routine.

Meteorologic Data Sources



(##) = number of stations

Figure 1



FLOOD FORECASTING PROCEDURES

Figure 2

1. DATEK Data

At present the data telemetered from automatic stations by telephone lines, both hydrometric and meteorologic stations, is collected by mini-computer system which is equipped with two auto-dialers. The system can be programmed to call the stations at varying frequencys and intervals. The system prints the data out on a dedicated terminal in the R.F.C. office as it is received. The system also archives the data and can generate historical listings of the data from the individual stations. Unfortunately, at present the mini-computer system is not interfaced with any of the computing systems used for running our forecasting models. The R.F.C. is currently working on the development of an integrated system.

2. GOES Data

The data telemetred by GOES platforms is obtained by dialing up the NESS computer in Maryland and establishing a link between that computer and a terminal in the R.F.C. office. The R.F.C. uses a Digital LA120 terminal equipped with a dial-up modem to access outside systems. The data that has been transmitted from the R.F.C.'s GOES DCP's and the other agencies's GOES DCP's to the NESS computer is transmitted from NESS to our terminal and printed out. The data that is printed out is unformatted and undecoded. The undecoded data is also stored, temporarily, on a floppy disk as it is transmitted from Maryland. The data is then

transmitted from the temporary storage device to the University of Alberta computing system. The R.F.C. has written a program, that operates on the University of Alberta system, which decodes data received from the various GOES DCP's and then produces a report which the duty forecasters can refer to. This program also sends the decoded data and the raw data to magnetic tape for permanent storage. The raw data from the GOES DCP's can be decoded manually but this is a very time consuming task.

One of the advantages of the GOES system is that the NESS computers in Maryland act as a central clearing house for all the data transmitted by all GOES DCP's. The R.F.C. has made arrangements with several other agencies operating GOES DCP's so that data from their stations is placed in the R.F.C. file on the NESS computer. This enables us to access meteorological data from 4 stations operated in northern Alberta by the Alberta Forest Service, and 3 stations operated in Montana by the Bonneville Power Administration. We also have permission to obtain data from several stattions operated by B.C. Hydro.

3. SNOTEL Data

Data from the SNOTEL network is obtained by dialing up the U.S.S.C.S. central computing system in Portland, Oregon. using the dial-up terminal. A report containing the most recent readings for several meteorological stations operating in northern Montana is then transmitted to the R.F.C. office.

A copy of this report is filed at the R.F.C. office.

4. **Banff Park Data**

The data from the 3 automatic meteorologic stations operated in the Banff National Park by the federal Park Service is available to the R.F.C.. The sites are on mountain tops. The Park Wardens use the data for an avalanche forecasting program. The R.F.C. obtains the data by using using the dial-up terminal to access an electronic storage device located at Sunshine Ski Village. This device stores several days worth of data. Data is transmitted from the Parks's sites to the central station by radio. The R.F.C. has a meteorologic site at Sunshine Ski Village, so it is convenient to use the storage device to hold data from this site as well. This telemetry approach for the Sunshine site was selected because of the convenience and because it was less costly then using other types of telemetry.

5. **Alberta Forest Service Data**

The Alberta Forest Service observer data is collected twice a day at the fire towers and once a day at the forestry ranger stations. The ranger stations operate year round, the fire towers are only operated during the summer. The observers report to regional stations by way of radio, the regional stations then transmitt the data by a dedicated landline to the central A.F.S. computer in Edmonton. The R.F.C. and A.E.S. have "drops" (terminals which receive, but

do not send data which are on the A.E.S. network.

6. Atmospheric Environment Service Data

Data from the Atmospheric Environment Service Synoptic stations is obtained by using a telex terminal to access the Alberta Weather Centre computer. Weather forecasts and Advisories are also obtained through this system. Other A.E.S. observers are contacted directly by telephone. Direct dialing of A.E.S. observers is not a routine operation, but sometime used during particularly heavy rainfall events or when the precipitation has fallen in an area not covered by other networks. The A.E.S. network provides good coverage of the plains areas of Alberta, which is not covered by our automatic network.

3.02 SSARR Meteorologic Data Requirements

Once the meteorologic data is received at the R.F.C. office, checked, decoded and archived some information must be extracted to use as input for the SSARR model. The SSARR meteorologic and hydrometric data sets must be updated daily, to provide routine forecasts, and to be prepared for possible flood forecasting. The following describes the meteorological data requirements of the SSARR model, and how the raw meteorological data is processed into input data for the SSARR model.

To perform a watershed simulation the SSARR model requires the following meteorological data;

1. Mean watershed precipitation.
2. Temperature.
3. Evapotranspiration Index.
4. Melt Rate data.

3.03 Mean Watershed Precipitation

The primary meteorologic input required by the SSARR model is a mean estimation of the areal precipitation over the watershed to be simulated. Precipitation data can be input into the model either as a mean estimate for the entire watershed, or as individual station values. In the latter

case the model calculates an areal average on the basis of weights assigned to those individual stations. Operationally the R.F.C. uses both techniques.

The station weighting approach offers the benefits of being objective and quick. It requires a fairly dense network of stations with similar reporting periods. The R.F.C. uses a Thiessen Polygon approach to determining station weights. The weights determined for each station in the watershed are specified to the model as a percentage. The forecaster then inputs the individual precipitation amounts recorded at those stations and the model calculates the watershed average.

The alternate approach is more subjective and time consuming. The forecaster plots the precipitation amounts on a map of the watershed and constructs an isohyetal map. An estimate of the average watershed precipitation is then prepared from this map. The subjective quality of this approach allows the forecaster to consider precipitation data from stations with varying reporting periods in his analysis, as well as any other information they feel is relavent ie. topograpy, storm direction, etc.. Estimates can vary between forecasters.

This past forecast season was the first time that the R.F.C. used an objective approach to determining mean watershed precipitation. The objective approach was used for the upper Red Deer River watersheds where the density of automatic precipitation stations is 1 station per 280 square

Kilometres, and the Paddle River watershed where the station density is 1 station per 160 square Kilometres. The results were quite good. Comparisons of mean watershed precipitation estimates produced by the model using the objective approach were comparable to the subjective estimates of forecasters. Previous work indicated that, given the same data, the variation between estimates prepared by different forecasters was usually as great or greater then the variation between any one forecaster's estimate and an estimate prepared using an objective technique.

The runoff coefficient calculated by the SSARR watershed simulation is a function of rainfall intensity and the relative wetness of the watershed. When entering precipitation data into the model the time interval between entries must be brief enough to accurately reflect the intensity of the precipitation. The R.F.C. has selected 6 hour intervals for several reasons;

- historical six hourly precipitation data was available for calibration purposes.
- Six hourly data seems to be adequate enough to reflect storm intensity.
- a briefer interval would increase the data handling load of the forecasting team, and increase the cost of the simulation runs.

As data from the automatic stations is available hourly, we are able to use that data directly for those areas where the objective station weighting technique for determining mean watershed precipitation is used. Hourly data from the auotmatic stations, and A.F.S. and A.E.S. data, is used for those areas where the subjective approach is used to determine mean watershed precipitation. The time period between observatations at the A.E.S and A.F.S. observer stations is greater then six hours. To use that data, the forecaster must make some estimates of how the observed precipitation was distributed in time. Normally the forecaster uses the data from the automatic stations to estimate how the other data was distributed in time.

The R.F.C. does not input forecasted precipitation values during routine operations. In a flood forecasting situation simulations might be run using estimates of anticipated precipitation, but flood forecasts or warnings are not issued on the basis of forecasted precipitation. The R.F.C. is in close contact with both the A.F.S. and A.E.S. weather forecasters.

3.04 Temperature Data

The SSARR model uses temperature data for several purposes;

- Temperature data is used to determine what percentage of

the precipitation fell as rain and what percentage fell as snow. The model calculates a "rain-freeze" elevation . those parts of the watershed that are below that elevation will be assumed to receive any precipitation that falls as rain, above that it will be assumed to be snow. The original SSARR model required temperature data for one station at a specified elevation. It then determined temperatures at other elevations by lapsing temperatures at a fixed rate. The "rain-freeze" temperature itself is determined in the calibration process and more or less fixed, usually the R.F.C. uses a value of 35° farenheit.[1] The R.F.C. has modified the program to accept temperature data from two stations at different elevations in the watershed. The model calculates a lapse rate on the basis of the the temperature difference between the two stations and uses that lapse rate to determine the "rain-freeze" elevation. This modification is most effective if there is a substantial difference in the elevation of the two stations.

- Temperature data is used to determine what part of the watershed is experiencing snowmelt and what part is not. A melt elevation is calculated in the same fashion that a "rain-freeze" elevation is determined, using the same

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[1] A true metric version of SSARR is not yet available. The R.F.C. uses a "mixed-mode" version that accepts meteorological input in SI units, but then converts the data and does the actual calculations in British units.

lapse-rate calculation modification. The R.F.C. generally uses a temperature of 32° farenheit to determine the melting elevation.

- Temperature data is used to determine how much snow will be melted. Melt rates are input into the model as millimetres of melt per degree day. The model uses the temperature data to determine the number of degree days per calculation interval.

The R.F.C. inputs temperature readings into the SSARR model at 6 hour intervals, the actual time of the reading is selected to be in the middle of the calculation interval. Thus, for a simulation run with 6 hour calcultation intervals starting at 00:00 hours on day 1 and running to 24:00 hours on day 1, temperature data would be input for 03:00 hours, 09:00 hours, 15:00 hours, and 21:00 hours. We have found that this frequency of temperature data is important to reflect diurnal fluctuations in snowmelt and to accurately differentiate between snow and rain during a storm. Previously, the R.F.C. only used minimum and maximum temperature data.

The snow melt simulation requires temperature data, so the forecaster must input estimates of future temperatures (normally 2 to 3 days worth of data) if they want to simulate the watershed for that future period. If estimates of temperature data were not entered the model would assume

temperatures of 0° farenheit over the entire watershed and assume that all rain would fall as snow, and no snow would melt.

3.05 Melt Rates

The determination of the correct melt rate to use in the SSARR model is a major area of concern for the R.F.C.. Operationally, two techniques are used at the R.F.C. to determine melt rates;

- an Antecedent Temperature Index Approach
- an approach involving snowpillow data.

The antecedent temperature index approach essentially determines melt rates on the basis of accumulated degree days, with some corrections for the time of year. Degree days are accumulated at selected stations, starting sometime well before the snowmelt season when the melt rate is assumed to be 0. Each day the new accumulation is put through a mathematical equation, which involves the previous days melt rate, and a new melt rate is determined. The technique has not been very successful in indicating when a sudden increase or decrease in the melt rate has ocurred. It is fairly effective in indicating the general trend of snowmelt.

The snowpillow approach is the preferred technique for determining melt rates for operational forecasting. In this

approach the actual amount of melt as measured by the pillow is divided by the number of degree days recorded at the site, all meteorologic stations equipped with snowpillows are also equipped with temperature sensors. The snowpillow approach indicates the general trend of snowmelt and will indicate when there is a sudden increase or decrease in the melt rate. Problems with this procedure are more attributable to snowpillows then the technique itself. Delayed reaction times to accumulation and depletion, problems with "bridging" over the pillow, and diurnal fluctuations in the snowpillow readings are some of the problems that can make this technique difficult to use.

Despite the problem with the techniques the R.F.C. has been fairly successful in using both approaches to model snowmelt.

Both techniques rely upon the previous day's data so the melt rate that is determined is for the previous day. To have the simulation cover several days into the future the forecaster must extropolate from the recent trend to estimate melt rates for that future period. Only one melt rate value per 24 hour period is input. That melt rate is distributed throughout the 24 hour period because it is multiplied by the degree days, as determined by the 6 hour temperatures.

3.06 Evapotranspiration Index

As mentioned earlier the runoff coefficient used by the SSARR model is a function of rainfall intensity and relative watershed wetness. Watershed wetness is indicated by a soil moisture index. Determining the exact nature of this relationship for different watersheds is a major part of the calibration process. For the real time simulation of a watershed it is necessary to specify to the model an evapotranspiration index, this ETI is used to deplete the soil moisture index. Periods of precipitation replenish the soil moisture index. The R.F.C. has developed a formula that uses windspeed data, humidity data, maximum temperature and the time of year for the real time determination of an ETI. The forecaster extracts the necessary data from selected stations, calculates the ETI, and then inputs the value into the SSARR model. Like the melt rate, the ETI is only determined on a daily basis, and because it is based on yesterday's data values must be projected into the future. A previously determined distribution is specified to the model and used to distribute the ETI throughout the 24 hour period.

Part 4 Interactive SSARR

The R.F.C. selected the SSARR model for operational forecasting in 1975. At present the R.F.C. uses SSARR to simulate most of the headwaters of the South Saskatchewan River and parts of the Athabasca and North Saskatchewan basins. This involves the simulation of over 40 individual watersheds.

Originally SSARR was designed to be run as a "Batch" program. The R.F.C. became aware in 1981 that a more modern "Interactive" version of the program was available, and began to investigate this version. Hydrologicaly the two versions are identical, the difference is in their data organization and structure. It was decided that the "Interactive" version offered many operational advantages over the "Batch" version and the newer version has become the operational model at the R.F.C.. The R.F.C. has adopted the convention of referring to the interactive version of the model has ISSARR and the batch version has BSSARR.

To understand the benefits of ISSARR over BSSARR some basic understanding of the SSARR model is necessary. To do a SSARR simulation several types of information are required.

1. Information about the configuration of the system to be simulated. This would include the configuration of the various watersheds, summing points, river reaches, lakes and reservoirs in the system.

2. A description of the physical characteristics of the various

points in the configuration. This would include such information as stage discharge and stage storage relationships, travel times for river reaches, and runoff characteristics of the watersheds being simulated. Some of this information would have been derived from the calibration process.

3. Information controlling the output of the run. This would include information about the types of hydrographs and reports that were desired.

4. The data that the simulation would be based upon. This would include all the meteorological information described in **Part 3**, as well as the hydrometric information that was required for the run.

5. Data describing the initial condition of the watersheds, river reaches, and lakes and reservoirs at the beginning of the simulation. The SSARR model can be run so that a new set of initial conditions is automatically output. A forecaster working on day 3 might make a simulation run beginning on day 1 and have it continue three days into the future, thus ending the run on day 6. That run would use the initial conditions for day 1. When the forecaster made that run he could ask the model to ouput a new set of initial conditions for day 3, the next time the forecaster made a run he could then start the run on day 3 using the new initial conditions. This prevents the runs from becoming overly long. The forecaster can also make adjustments to the initial

conditions, so it is possible to match the simulation closely with the actual situation at the beginning of the run. Data determining the length of the run and when the initial conditions should be output are normally included with the initial conditions.

In BSSARR all this information would have to be submitted to the computer, in one "batch", each time a simulation run was to be made. SSARR was originally designed to be run using cards, and although cards are not normally used now, BSSARR requires that all 5 types of data be entered in a rigid card type format. These "cards" are then all submitted to the computer to make a simulation run. Operationally the forecaster must alter and make additions to those parts of the set of "cards" that contain the data they wish to update. For routine operations the forecaster would normally be changing and updating the information described in points 4 and 5.

For routine operations, even using video display type terminals, this approach had some drawbacks;

- The rigid format required for the data, can be a source of errors. A single keypunching error can make the results of a simulation meaningless, often the error will not be discovered until the the run has been made and the results are being analyzed.

- The awkwardness of the format makes it more convenient to use a few BSSARR models which include a large number of watershed

simulations and river routings in each model, rather then a large number of models with only a few simulations or routings in each model. This is because each model must have its own set of initial condition cards, data cards, and output control cards. Maintaining a large number of such data sets is confusing, and can result in duplication of effort. To some extent clever design of the data sets can reduce this problem, however the R.F.C. found that BSSARR forced us to compromize between conveniently sized simulation models and the problem of maintaining too many data sets.

- The R.F.C. plans to move to an automated data base type operation, eliminating the need for the forecasters to manually key in much of the data used for simulations. BSSARR would not easily be interfaced with such a system.

The interactive version of SSARR eliminates these problems, and offers other advantages as well. In ISSARR all the data used by all the simulations (Points 1 through 5) is stored in one common data base. Additions of different types of data, or altering data in this data base can be done in various ways, depending on the nature of the data.

Altering the data described in points 4 and 5 is done in an interactive fashion. For example, if a forecaster wants to input new precipitation data for a station or watershed they run a small subroutine which will ask the forecaster for the date and time of the data that they are going to input. Once the date and

time are entered the system will then prompt the forecaster for the station name or watershed name. The forecaster can enter an individual name or the name of a list of stations or watersheds. The list having been created previously and stored in a different part of the data base. The system will then prompt the forecaster to enter the precipitation value for that station or watershed, or prompt them for data for each of the stations, one by one, on the list. The data itself can be entered in a free format and the system drastically reduces errors that result from keypunching mistakes. Slightly different subroutines are used for updating hydrometric data and adjusting initial conditions, but the procedures are similar .

Unlike BSSARR, which requires numeric station identifiers, ISSARR recognizes alphabetic characters as well. Station names are much more easily recognized. Routine updating of data using ISSARR is very "user friendly" in comparison to BSSARR.

To make a simulation run using ISSARR the forecaster will use a small subroutine which asks him for the time specifications of the run, start date, end date and calculation interval. The system will then prompt him for a model name. The model being a description of the configuration of watersheds, river reaches, lakes, reservoirs and other points in the river system the forecaster is simulating. This model was previously determined and is stored in the data base. The actual description of the characteristics of the individual stations and watersheds in the model are also stored in the data base. This creates a kind of

master catalog of watersheds, river reaches, reservoirs and lakes, and summing points in the data base. A multitude of various station and watershed configurations can be described in a multitude of configuration models. One station can be used in many different configuration models but need only be described once in the catalog.

Once the forecaster has specified the model they whish to run, the system will do all the watershed simulations contained in that model. This occurs immediately and the results will be printed out at the terminal the forecaster is working on. If the forecaster is not happy with the results of the watershed simulations, they can go back and make the changes to the data or initial conditions that they feel will improve the results and rerun the watershed simulation part of the model. If the forecaster is happy with the results of the watershed simulation they can request that the river routing portion of the model be executed. This will occur immediately and the desired reports and hydrographs will be generated at the terminal.

Operationally, the R.F.C. runs several large configuration models three times a week. Combined these "macro" models contain every station in the description catalog. For convenience sake the "macro" models are divided by river basins. There is a macro model for the Bow, Oldman, Red Deer, North Saskatchewan and Athabasca basins, and a routing model used to forecast flows on the South Saskatchewan at the Alberta-Saskatchewan border. The major purpose of running these macro models is to maintain

updated sets of initial conditions. Initial conditions for each watershed, river reach, lake and reservoir are stored in the common data base. Running the six models three times a week, and keeping the common meteorological and hydrometric data base up to date, means that the R.F.C., at any given time can run one of over 45 smaller, more convenient mini-configuration models.

The R.F.C. has small configuration models which generate forecasts for specific locations, models which route watershed simulation results to specific locations, models which route recorded hydrometric data to specific loacations, models specifically for generating reservoir inflow forecasts and models specifically for routing reservoir releases. Some of these models might never be used in a forecast season, but they will always be available should a situation requiring them develop. Maintenance of the data sets and initial conditions required by the "macro" models means that the smaller models are always ready to run. Proper documentation of the available configuration models is essential.

ISSARR has proved to the R.F.C. that it is a vastly more flexible system and consideral improvement over BSSARR as an operational forecasting tool. The R.F.C. is moving towards an automatic data acquisition system which will be able to directly input data in the ISSARR data base. This will free the present duty forecasters from a large data handling work load and allow us to generate forecasts much more quickly.

Part 5 Future Plans

The rapid development of the automatic networks proposed by the R.F.C. created something of an embarrassment of riches. The data handling capabilities of the R.F.C. were, and are taxed to the limit. Handling the meteorological data alone requires that the forecasters on duty, remove data from many different sources, record and archive that data, prepare it for SSARR, and then keypunch it in. ISSARR helped reduce some of the workload, but the R.F.C. has been forced to look at any forecast procedure additions mainly in terms of the consequences such an addition would have to the data handling load. Any additions to the automatic data collection network, beyond those already proposed, were simply not feasible. Still, the Alberta government is considering at least two major dam projects, one on the Oldman River and one on the Slave River and demands for real time forecasting services in the northern parts of the province are increasing.

The R.F.C. foresaw this problem of inadequate data handling capability at the same time as the South Saskatchewan network proposal and began working on improving the automatic data acquisition system. Unfortunately data handling did not improve as quickly as data acquisition. This fall the R.F.C. will begin testing an upgraded system which will automatically acquire, decode and archive all data acquired by telephone telemetry and most data acquired by GOES telemetry. The system will also do

quite a bit of processing of the hydrometric data (ie. calculate discharges and storages from gauge heights). In the near future the R.F.C. plans to have a data acquisition system that will not only be able to acquire and process data from all sources, but which will also have the capability to run ISSARR or interface with a system with such a capability. Such a system will eliminate the need to enter data into the ISSARR data base manually, and the ISSARR system will be mainly used for editing data that had been automatically input. Improvements in our automatic data handling capability are probably the immediate major concern at the R.F.C.

Another long term project which is just coming on stream is the weather radar project which the R.F.C. has been developing in conjunction with the Alberta Research Council. The radar project was originally entered into as part of the proposal for the Dickson Dam. The Research Council operates a radarjust south of Red Deer, its coverage extends almost to the headwaters of the Red Deer, south to Calgary and north to Edmonton. The Research Council has developed a system which will generate real time precipitation estimates, in fifteen minute intervals, for any one kilometre point in the coverage area. A colour monitor in the R.F.C. office will display the latest precipitation map generated by the radar, or display a series of past maps in sequence. The latter animation type display will allow the forecaster to see how a storm is tracking through the coverage area. A number of other products will also be produced. The Research Council system should be compatible with radars that A.E.S. has proposed for the

Calgary and Edmonton areas. The system will be ready for operational use in the spring of 1984.

Some other areas that the R.F.C. is concentrating on are improving the forecasting of snowmelt. Plans are being made to include nuclear type snow gauges at some of the meteorological sites, to see if they are an improvement over the snow pillow. Solar radiation sensors are also to be installed at some sites to see if this data will help to improve melt rate calculations. Much of our research into the snow melt problem is being done using data from the Marmot Creek Research Watershed located in the mountains west of Calgary. Improving the forecasting of water supply from plains area snowmelt is another area which the R.F.C. is concentrating on, most work here has been more stochastic then deterministic.

The R.F.C. plans to continue to use the SSARR model, and continual to make changes to make the model more applicable to the Alberta situation. Most changes will probably be oriented more to improve the operational aspects of ISSARR, rather then modifications to the hydrologic computations.

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U.SPORNS- B.C.HYDRO.-

ON THE USE OF METEOROLOGICAL DATA IN OPERATIONAL SHORT-TERM RUNOFF FORECASTING.

BC HYDRO HAS DEVELOPED A CONCEPTUAL RUNOFF SIMULATION MODEL FOR DAY TO DAY RESERVOIR OPERATION. THE MODEL, CALLED "FLOCAST" IS BASED MAINLY ON THE STANFORD RESEARCH MODEL.IT PROVIDES A SIMPLE COMPUTERIZED OPERATIONAL TOOL TO OBTAIN MEAN DAILY RUNOFF FOR ABOUT 20 DRAINAGES USING CURRENTLY AVAILABLE INPUT PARAMETERS. THE PROGRAM IS RUN DAILY THROUGHOUT THE YEAR AND PROVIDES LOCAL INFLOWS 5 DAYS AHEAD.

ALL INPUT PARAMETERS ARE METEOROLOGICAL PARAMETERS, WITH THE EXCEPTION OF THE MEASURED INFLOWS.THIS YEAR-ROUND OPERATION IS PERFORMED BY 2 METEOROLOGISTS AND 2 TECHNICAL SUPPORT STAFF MEMBERS.

IN THE DAY TO DAY OPERATING MODE, THE FLOCAST MODEL EMPLOYS 5 DAYS OF HISTORY AND 5 DAYS OF FORECASTS.TYPICAL OUTPUT FOR EACH DRAINAGE CONTAINS 5 LINES OF HISTORY [DAY -5 TO -1] AND 5 LINES FOR THE PREDICTED DAYS, [DAY 1 TO 5] , WHERE DAY 1 IS TODAY.THE HISTORICAL DAYS ARE BEING USED FOR RUNNING CALIBRATION.MANUAL ADJUSTMENTS ARE MADE AS REQUIRED.

THE FLOCAST MODEL DIVIDES EACH DRAINAGE INTO 200M ELEVATION BANDS. UP TO 18 ELEVATION BANDS CAN BE USED.THIS ARRANGEMENT IS MOST PRACTICAL FOR MOUNTAINOUS DRAINAGES, AS IT PERMITS THE USE OF CERTAIN BASIN-WIDE PARAMETERS, SUCH AS SNOWLINE AND FREEZING LEVEL.A YEAR-ROUND RUNNING ACCOUNT IS KEPT BY THE FLOCAST MODEL OF SNOWPACK WATEREQUIVALENTS FOR EACH ELEVATION BAND. DAILY DELETIONS [SNOWMELT] AND ADDITIONS [SNOWFALL] ARE RECORDED.

ON THE DAILY OUTPUT SHEET FOR EACH DRAINAGE,[5 LINES OF HISTORY FOLLOWED BY 5 LINES OF FORECASTS], INPUT PARAMETERS ARE GENERALLY PRESENTED ON THE LEFT,MODEL OUTPUT ON THE RIGHT.THE SEQUENCE FROM LEFT TO RIGHT IS ,AS FOLLOWS : NAME OF DRAINAGE, MONTH AND DAY,MIN. AND MAX AIR TEMP. [VALLEY LOCATION],SNOWLINE ELEVATION,FREEZINGLEVEL HEIGHT, SNOWMELT FACTOR,AVERAGE BASIN PRECIPITATION,BEGINNING AND ENDING OF AVERAGE BASIN PRECIPITATION,THEN THE LOCAL DRAINAGE BASIN INFLOW [PREDICTED OR CALCULATED],AREA SUBJECT TO RAIN RUNOFF,AREA SUBJECT TO SNOWMELT RUNOFF,LOWER ZONE SOIL MOISTURE STORAGE CAPACITY [IN MM],GROUNDWATER STORAGE [IN MM], INTERCEPTION [IN MM],POTENTIAL AND ACTUAL EVAPOTRANSPIRATION [IN MM],DAILY RAIN-RUNOFF [IN CFS],DAILY SNOWMELT RUNOFF [IN CFS],DAILY GLACIERMELT RUNOFF [IN CFS],DAILY BASINWIDE EVAPORATION [NEGATIVE,IN CFS],BASEFLOW [IN CFS], AND FINALLY THE TOTAL OF RECORDED MINUS PREDICTED RUNOFF [EITHER NEGATIVE -OVERFORECAST- OR POSITIVE -UNDERFORECAST]

WHILE THE MODEL CONSIDERS ALL OF THOSE PHYSICAL PROCESSES WE THINK ARE INVOLVED IN THE RUNOFF PROCESS, THE ONLY INFORMATION AVAILABLE TO US ON A DAILY BASIS AS INPUT ARE AIRTEMPERATURE. AND PRECIPITATION.A FURTHER DRAWBACK IS THE FACT,THAT ALL OF THESE OBSERVED METEOROLOGICAL PARAMETERS ARE POINT VALUES, USUALLY FROM SOME VALLEY STATION, AND NOT AVERAGE BASIN-WIDE PARAMETERS REQUIRED FOR RUNOFF SIMULATION.

IN ORDER TO OBTAIN BASIN PRECIPITATION FROM THE AVAILABLE POINT MEASUREMENTS IN MOUNTAINOUS DRAINAGES UTELIZING ALL INFORMATION , WE HAVE DEVELOPED THE FOLLOWING METHOD :

FOR EACH CLIMATE STATION TO BE USED FOR A PARTICULAR DRAINAGE WE FIRST DETERMINE THE RATIO OF MEAN ANNUAL BASIN PRECIPITATION (FROM HISTORICAL FLOCAST VALUES)OVER MEAN ANNUAL CLIMATE STATION PRECIPITATION.AS PRECIPITATION GENERALLY INCREASES WITH HEIGHT AND AS MOST CLIMATE STATIONS ARE LOCATED AT LOW LEVELS, THIS RATIO WILL ALWAYS BE GREATER THAN ONE.

THE RATIO OF BASIN PRECIPITATION OVER POINT PRECIPITATION IS THEN MULTIPLIED BY A MONTHLY STATION WEIGHT FACTOR.THIS FACTOR IS A PRODUCT OF MULTIPLE CORRELATION TECHNIQUES USED IN OUR SEASONAL RUNOFF VOLUME FORECASTING PROCEDURES.THE RESULTING DAILY STATION WEIGHT FACTORS ARE THEN USED ROUTINELY TO CALCULATE THE DAILY BASIN PRECIPITATION VALUES AS INPUT TO FLOCAST.

FOR THE CALCULATION OF DAILY SNOWMELT AND GLACIERMELT A CERTAIN AIR TEMPERATURE MUST BE ASSIGNED TO EACH ELEVATION BAND.TWO SOURCES ARE AVAILABLE FOR THIS PURPOSE : DAILY MAXIMUM TEMPERATURE AT A CLIMATE STATION AND THE FREEZING LEVEL HEIGHT FROM A NEARBY RADIOSONDE STATION.IF BOTH VALUES ARE AVAILABLE, THE MODEL WILL ASSIGN THE PROPER LAPSE RATE.ARRANGEMENTS HAVE BEEN MADE TO ELIMINATE UNREASONABLE VALUES. IF ONLY ONE OF THESE PARAMETERS IS AVAILABLE, A LAPSE RATE OF 5,47 DEGR C.PER 1000 METERS IS ASSUMED.REPRESENTATIVE ELEVATION BAND TEMPERATURES MAY BE INCREASED BY 2 DEGR.C. IF EXPOSED TO SUNSHINE.

MONTHLY SNOWCOURSE READINGS AVAILABLE FROM JANUARY THROUGH MAY HAVE BEEN CORRELATED WITH THE SNOWPACK WATEREQUIVALENT VALUES GENERATED BY FLOCAST FOR EACH ELEVATION BAND.WEIGHTED CORRECTIONS TO THE MODEL ARE MADE AS SNOWCOURSE DATA BECOMES AVAILABLE.

SNOWLINE FLIGHTS ARE USUALLY CONDUCTED TWICE A YEAR DURING THE FRESHET FOR ALL DRAINAGES.SNOWCOVER DATA OBTAINED FROM THESE FLIGHTS IS USED TO CALIBRATE THE SNOWCOVERED AREAS GENERATED BY FLOCAST.NOAA/NESS IN WASHINGTON D.C. PROVIDES THE SNOWCOVERED AREA FOR THE MICA DRAINAGE (COLUMBIA RIVER) WHICH THEY DERIVE FROM WEATHER SATELLITE IMAGERY.THE TENDENCY HAS BEEN,THAT SATELLITE DERIVED SNOWLINES ARE TOO HIGH EARLY IN THE FRESHET, DUE TO THE INABILITY TO RECOGNIZE SNOW UNDER CONIFER-TYPE TREE COVER,AND TOO LOW LATE DURING THE FRESHET ,DUE PROBABLY TO THE INCLUSION OF BARE ROCK AREAS.THESE ANALYSES ARE CONDUCTED BY SUBJECTIVE ASSESSMENTS.

VERIFICATION OF THE RESULTS OF LOCAL RUNOFF PREDICTIONS FOR SOME 20 DRAINAGES IN BRITISH COLUMBIA DURING 1982 ARE AS FOLLOWS:

FOR COASTAL AND VANCOUVER ISLAND DRAINAGES ,PREDOMINANTLY RAINRUNOFF: (PERCENT ERROR)

DAY 1 TO 5 : 49% , 53% , 60% , 67% , AND 74% .

FOR INTERIOR DRAINAGES , MAINLY SNOWMELT RUNOFF :

DAY 1 TO 5 : 26% , 28 , 30 , 32 , AND 34% .

PRIOR TO THE INTRODUCTION OF THE FLOCAST MODEL INTO BC HYDRO'S OPERATION,NORMAL MEAN DAILY INFLOWS WERE ASSUMED. THE IMPROVEMENT OF THE FLOCAST OUTPUT VERSUS NORMAL MEAN VALUES IS AS FOLLOWS: (IN PERCENT)

FOR MAINLY RAIN RUNOFF BASINS :

DAY 1 TO 5 : 59% , 55% , 48% , 42% , 34%.

FOR MAINLY SNOWMELT RUNOFF BASINS :

DAY 1 TO 5 : 19% , 17% , 15% , 13% , 11%.

WHILE WE CONSIDER THE PERFORMANCE OF OUR FLOCAST MODEL IN DAY TO DAY RESERVOIR OPERATION AT THIS POINT IN TIME OF GREAT HELP, THERE IS UNDOUBTEDLY ROOM FOR IMPROVEMENT. HAVING OPERATED THE MODEL IN A HANDS-ON MODE SINCE 1969 WE BELIEVE THAT IMPROVEMENTS MUST BE MAINLY IN THE QUALITY OF INPUT PARAMETERS,RATHER THAN THE MODEL ITSSELF.THE MAIN FAULTS WITH THE INPUT PARAMETERS ARE POOR DETECTION OF ACCURATE BASIN PRECIPITATION VALUES DUE TO VERY INADEQUATE NETWORKS, AND OUR INABILITY TO PREDICT QUANTITATIVE PRECIPITATION WITH SUFFICIENT ACCURACY.

PRECIPITATION OBSERVATIONS FROM THE CLIMATE NETWORK ARE ALMOST ENTIRELY FROM LOW-LEVEL STATIONS. NETWORK DENSITY IS GENERALLY LESS THAN HALF OF WMO MINIMUM RECOMMENDATIONS FOR MOUNTAINOUS AREAS.MANNY OF OUR DRAINAGES DO NOT HAVE A SINGLE CLIMATE STATION WITHIN ITS BOUNDARIES.DAM SAFETY STUDIES CONDUCTED RECENTLY BY BC HYDRO CAME TO THE SAME CONCLUSIONS,AND RECOMMENDED DRASTIC NETWORK IMPROVEMENTS TO PROVIDE REAL-TIME DATA FROM OUR OPERATIONAL DRAINAGES.AS A RESULT A TOTAL OF ABOUT 60 DCP STATIONS WERE INSTALLED THROUGHOUT BRITISH COLUMBIA FROM WHICH HOURLY, IN SOME CASES HALF-HOURLY, OBSERVATIONS ARE AVAILABLE IN NEAR-REAL-TIME. AS A MATTER OF POLICY AIR TEMPERATURE AND PRECIPITATION SENSORS ARE INSTALLED AT ALL DCP SITES, REGARDLESS IF THE SITES ARE MAINLY HYDROMETRIC, OR AT A SNOWCOURSE.

THE REMAINING PROBLEM IS THE QUALITY OF QUANTITATIVE PRECIPITATION FORECASTING.WHILE RADAR IS OF LITTLE PRACTICAL VALUE IN THE MOUNTAINOUS AREAS OF B.C., WE HAVE GREAT HOPES FOR IR GOES IMAGERY.METHODS DEMONSTRATED BY DR.DIANE INGRAHAM AT UBC ARE OF PARTICULAR INTEREST TO US, PARTICULARLY FOR OUR FLOODPRONE COASTAL DRAINAGES.EVEN A ONE OR TWO DAY PROJECTION OF THE MOVEMENT OF MAJOR RAINAREAS WOULD GO A LONG WAY TOWARDS IMPROVED DAM SAFETY OPERATIONS.

AN ECONOMIC AUTOMATED SYSTEM FOR ACQUISITION OF PRECIPITATION DATA

by

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ABSTRACT

A precipitation instrumentation package for measuring rainfall intensity at a fine time and space resolution is described. The package comprises a drop counter precipitation sensor (DCPS), a microcomputer-based data acquisition system (DAS), an intelligent data decoder (DD), and a software package (FASTPLOT), for data capture. The merits and demerits of the new system are discussed. Typical data are presented.

INTRODUCTION

Costs of recording rain intensity instruments in present use are of the order of $1000.00 for a complete station. Running costs are high, since conventional data collection systems require a high labor content for fieldwork and data capture, storage and presentation.

The result of these real cost components of running a rain gauge network has been that the data collected tends to be insufficient. Consequently Civil Engineers, in turn, use methodology for flood hydrology that is based on simplified assumptions, such as uniform spatial distribution of rain over significantly large catchment areas. Dynamic tracking of storms, storm models based on kinematics of cells within the rainstorm, and similar improvements, still await the advent of better spatial and temporal sampling of rainfall. Storm models lead to considerable improvements in estimates of runoff and pollutant washoff, a matter of great importance in flood and stormwater management.

Most rainfall intensity monitoring is at present based on tipping bucket rain gauges (TBRG). A conventional TBRG and associated chart recorders frequently give rise to errors, particularly when the recorder strip charts are translated manually into time series. Accordingly, we have developed an automated, low-cost, high-resolution, reliable, and intelligent system for rainfall data measurement, acquisition, and presentation.

Our precipitation instrumentation package is specifically designed to improve the understanding of rain, its occurrence and its effects on the environment. The package consists basically of four major parts: a precipitation sensor (DCPS), a microcomputer-based data acquisition system (DAS), an intelligent data decoder (DD), and a software package (FASTPLOT) for the base microcomputer.

The DCPS collects the rainfall and converts it into water drops of almost constant size. The drops are detected when they close an electric circuit. The DAS senses the drops and counts them over a programmable time interval, storing the counts temporarily in a single chip microcomputer. The DAS processes the time series and stores it on standard audio cassette magnetic tape. The cassettes are removed and transported to the central site to be read by the data decoder (DD). The time interval between cassette removals can be many months. The DD reads the information from the tape, verifies and communicates the rainfall time series to a computer for data processing via FASTPLOT.

PRECIPITATION SENSOR

The DCPS is a standard rainfall totalizer from Atmospheric Environmental Services (AES). The precipitation sensor is contained in two cylinders, denoted (1) and (2) in Figure 1. Cylinder (1) contains the sensor while cylinder (2) is used as the base, housing the instrument.

Molded as part of cylinder (1) there is a funnel (3) whose function is to collect the rain. The machined plexi-glass cylinder (4) is pierced by a stainless steel tube (5) that converts the water into drops. The lower part of the plexi-glass cylinder supports the sensor (6) which consists of two electrically conducting probes. The probes are gold-plated, mass-produced pins.

The probes are connected to an amplifier (7) which boosts the electrical signal produced when the drop is in contact with the sensor points. Connector (8) provides access to the electrical signal from the amplifier. Cylinder (1) may be separated mechanically as well as electrically from cylinder (2).

At the top of the funnel, inside cylinder (1), there is a removable coarse mesh screen (9) whose function is to trap leaves etc. Under this mesh, there is another fine mesh screen (10) to prevent dust from entering the stainless steel tube.

A clamp (12) secures the two-conductor cable (13) to the cylinder (2). The cable feeds the electrical signal to the DAS.

Limitations of the DCPS are as follows:

(a) For very high rainfall intensities, the flow changes from drops to a continuous jet. Tests show that, for the geometry presented here, continuous jet flow commences only well above 170 mm of rain per hour, which is a rare event. In Ontario such a rain intensity would last five minutes or longer, about only once every 100 years on the average. Of course, a smaller catching area would handle higher rainfall intensities.

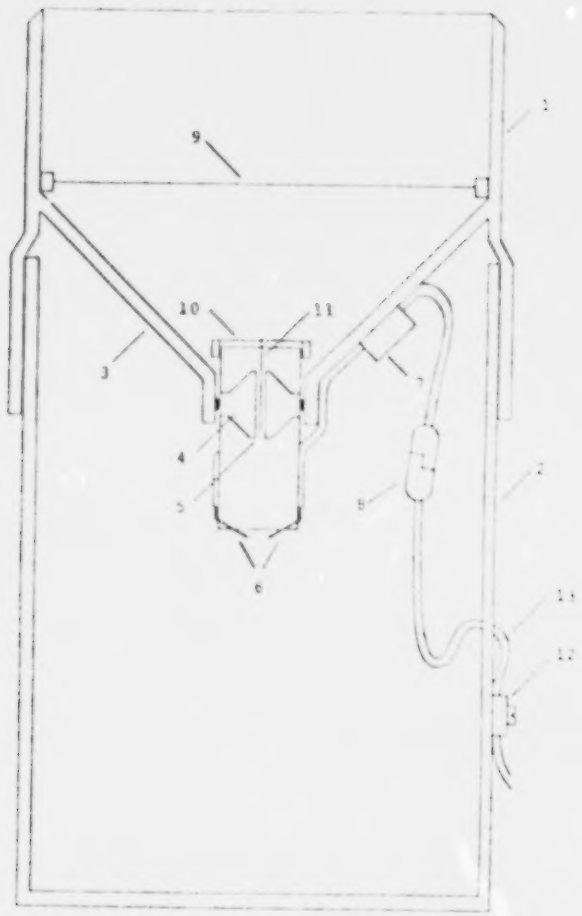

FIGURE 1
DROP COUNTER PRECIPITATION SENSOR

(b) The two meshes have to be partially wetted before the water can pass through the funnel. When the sensor is operated from the dry state, some water must be collected before water will pass through the tube. Also once the sensor is wet, some water must build up at the top of the tube to overcome the surface tension and then pass through the tube. The amount of water required from the dry state is approximately 0.10 mm of rain and the amount required to overcome the surface tension is approximately 0.01 mm of rain. These amounts are considered to be negligible in flood hydrology. Technical details of the precipitation sensor are listed in Table 1.

TABLE 1
DROP COUNTER PRECIPATION SENSOR
TECHNICAL DATA

Type	AES
Collection area	9998.03 sq.mm
Drop size:	
Mean	0.004681 mm of rain
Maximum rate	170 mm of rain/hr
Water retention from dry state:	
Mean	0.10 mm of rain
Dimensions:	
Height	365 mm
Diameter	115 mm

DATA ACQUISITION SYSTEM

The DAS was originally designed to collect and store information from the DCPS only and therefore contains only one channel. It is intended that other measurements, such as temperature, water conductivity and pH, and the like will be included in later developments. A block diagram of the DAS is shown in Figure 2. Its operation is as follows:

The microcomputer counts the number of drops during a time period known as the rain integration time. At the end of this time, the count is stored in the microcomputer RAM together with a time mark. Each data word occupies one byte (8 bits) so that the largest number that can be stored in one memory location is 255. However the precipitation sensor is capable of detecting over 10 drops per second which is more than 600 drops for a rain integration time of one minute. To cope with this number, we would require a word length of 10 bits, so an alternative was chosen: divide the total number of drops by four to reduce the range. Events of 240 mm of rain per hour are very unlikely in areas where the systems are operating at present. The instrument resolution is thus 0.01872 mm of rain per count, which is considered satisfactory as present data processing uses data from TBRG where the resolution is lower. The microcomputer performs the division by 4 using software; it may therefore by modified as required with simple program changes.

The 8748 microcomputer has 64 bytes of RAM. Of these, 40 are available to store up to 20 pairs of data (data sets) and the remaining space is used for the program execution. The first 8 locations are directly addressable by several instructions and some of them are used for the time mark counter, the memory pointer and the loop counter to determine the integration time.

The next 16 locations contain the program counter stack for up to 8 nested subroutines. The data collected and the time marks reside in the last 40 memory locations.

Every time this memory space is filled, the microcomputer turns on the cassette recorder and dumps the block of information onto magnetic tape. In order to save space in memory and on tape, the DAS represents the acquisition time as an incrementally coded time mark. The microcomputer stores data in RAM memory only when rainfall is detected or when the time mark counter equals 240 decimal. The integration time is software generated and is therefore easily modified to meet unusual requirements. In the present system it is one minute.

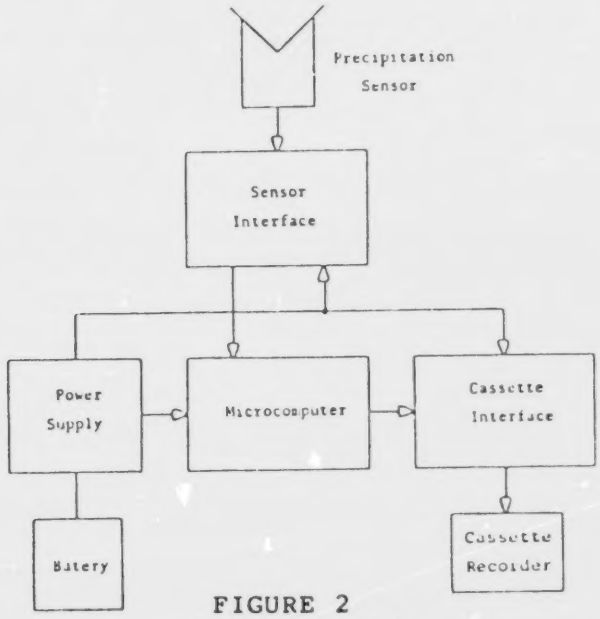

FIGURE 2
BLOCK DIAGRAM
DATA ACQUISITION SYSTEM (DAS)

The cassette interface contains the circuits needed to control the recorder power supply and to condition the signal to be recorded. The recorder is a mass-produced unit for audio purposes that has been modified slightly. In order to record the digital signal onto the tape, frequency shift keying (FSK) is used because of the limited frequency response of the recorder. Standard audio cassette tapes are used.

The microcomputer generates the FSK signal using software, and delivers it through one of its output pins to be recorded onto tape. Every character recorded comprises eight bits of informaticn, one start bit, one stop bit and one parity bit. The control bits are used in the data recovery stage. The Kansas City standard (6) for recording digital information on audio magnetic tape is used.

We have also developed a DAS for battery-only operation, the microcomputer is replaced by a CMOS version.

TABLE 2
DATA ACQUISITION SYSTEM TECHNICAL DATA

Microcomputer	Intel 8748
Storage media:	
Magnetic cassette tape	Audio
Modulation	Frequency Shift Keying (FSK)
Carriers	1.8 kHz for logical "0" 2.7 kHz for logical "1"
Baud rate	300 bits per second
Format	50 bytes per block 11 bits per byte
Data block	10 bytes of sychronism 20 bytes of data 20 bytes of timing
Measured error rate	Less than one error in 10E6 bits stored.
Integration time	Programmable
Period of unattended operation	7 days of rain (tape C-60 one side).
Operating temperature	+10 to +50 deg C. (for tape recorders)
Power requirements:	
Steady State	75 mA @ 5 V.D.C.
Peak	225 mA @ 5V.D.C. for 3 1/2 seconds when data is transferred to tape.
Battery back-up	17 hrs. Six "C" size rechargeable.
Dimensions:	
Height	10 cm
Width	17 cm
Depth	30 cm

The electronic components are assembled on a 5 cm by 7.5 cm single-sided printed circuit board. The circuit board, the transformer, the battery, and the cassette recorder are housed together in a metal case.

The unattended time period of the system depends basically on the tape capacity. The DAS stores approximately 17 blocks of information on one minute of tape. The number of data sets recorded depends on the duration of rain and not on the amount of rain. When the integration time is programmed to one minute, the system can be left unattended for more than 7 days of continuous rain or more than 4 years of no rain.

The microcomputer is fully dedicated to data acquisition and storage. However, these tasks use only a small fraction of the time, so the remaining time may be used to perform some data processing.

DATA DECODER

A microcomputer-based DD retrieves the information from the tape and transfers it to the central computer. A block diagram is shown is Figure 4.

The played-back signal is a distorted sinusoidal FSK signal. A second order band-pass filter at the input of the DD attenuates noise outside the band of interest. The filter also amplifies both signals, but the high frequency carrier is amplified slightly more than the low frequency carrier, to equalize the recorder frequency response.

After the input signal has been filtered and amplified, a phase locked loop together with a voltage comparator perform the signal demodulation. The digital signal at the output of the comparator is fed into the microcomputer through a testable input using conditional jump instructions.

The microcomputer receives the digital signal and converts it into parallel format, checks the validity of the data using the parity bit, and informs the user of any error detected. The information retrieved is converted from straight binary into ASCII and transmitted asynchronously to the central computer for data processing. Data transmission is at 1200 baud via the RS-232C interface.

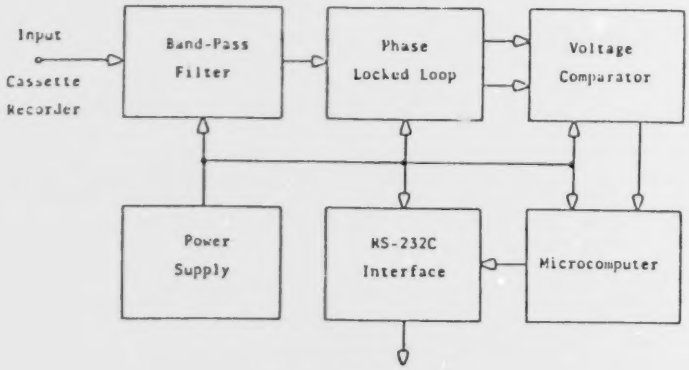

FIGURE 4. BLOCK DIAGRAM OF THE DATA DECODER (DD)

Every block of information recorded on tape is preceded by a synchronization block, consisting of at least ten characters of zeroes. To perform the data recovery, the microcomputer synchronizes with the start bit of each character and generates the required time delay to sample the rest of the bits at the centre of occurrence. The presence of the stop bit is checked for error detection. This type of synchronization ensures that small amounts of pulse-to-pulse jitter and frequency shifts have no effect on the data recovery. Tests performed show an error rate of one soft error in more than one million and one hard error in more than ten million bits stored.

When played back, the tape contains blocks of noise between tape information blocks. These blocks are introduced onto the tape when the microcomputer turns the cassette recorder on and off. The tape-use efficiency is reduced to just over 55% because of these blocks. The efficiency may be improved if circuitry is incorporated to achieve faster start and stop of the recorder drive mechanism.

DATA PROCESSING

After the block of information has been converted into ASCII format by the microcomputer, each of the 20 data sets comprises 2 numbers of 3 decimal digits each. The first number represents the acquisition time and second the amount of rain sensed in the previous integration time. To convert the series of numbers into meaningful information, the time and date when the tape was installed must be known. Figure 6 shows one complete block of information (40 words) and its interpretation. High rainfall is seen at the start and end of this block. The intensity increases then ceases for 10 hours and 11 minutes before another onset.

FASTPLOT is used to receive, interpret, store, process and present the information. FASTPLOT derives hyetographs for each one of the storms recorded at each monitoring site as shown in Figure 7. FASTPLOT has been written in FORTRAN for Radio Shack TR16 and PDP11/23 microcomputers, and BASIC for Apple II systems. Further processing is typically for stormwater management modelling. These models determine average, daily, monthly and annual amounts of stormwater runoff entering the receiving waters. The models are also used to investigate a wide range of design alternatives and strategies for minimizing pollutant overflows due to stormwater in the City of Hamilton. In the field program, rainfall intensity, stormwater quantity and quality samples are collected from various field stations located thoughout the city.

FIGURE 6
One complete block of information and its interpretation
Starting Time: October 5, 18:30 hours

0980050990181000421010464020 40
1030211040071050072400002400 00
2360172370632380982391402401 53
0011650021490031410041280051 03

FIRST NUMBER	SECOND NUMBER	TIME	DAY	DROPS	MM OF RAIN
098	005	20:08	5	10	0.0468
099	018	20:09	5	36	0.1685
100	042	20:10	5	84	0.3932
101	046	20:11	5	92	0.4307
102	040	20:12	5	80	0.3745
103	021	20:13	5	42	0.1966
104	007	20:14	5	14	0.0655
105	007	20:15	5	14	0.0655
240	000	22:30	5	0	0.0
240	000	02:30	6	0	0.0
236	017	06:26	6	34	0.1592
237	063	06:27	6	126	0.5898
238	098	06:28	6	196	0.9175
239	140	06:29	6	280	1.3107
240	153	06:30	6	306	1.4324
001	165	06:31	6	330	1.5448
002	149	06:32	6	298	1.3949
003	141	06:33	6	282	1.3200
004	128	06:34	6	256	1.1983

CONCLUSIONS

Substantial improvements in stormwater management are achieved when more and better information is available. The need is to increase the number and quality of sampling sites without increasing capital and maintenance costs appreciably, by using low-cost systems that require little maintenance, inexpensive data processing, and which provide the user with information of higher resolution.

At present, twelve drop counter precipitation sensors are in use in Hamilton, as part of the hydrometeorological field program of the Computational Hydraulics Group at McMaster University. Also six sensors were used in different precipitation sampling sites across Ontario in studies on acid rain, six are in use in Toronto, while others are to be used in Ottawa, Halifax, the Northwest Territories, Kentucky and in Norway.

Some of the sensors used in the Hamilton area operate at the same sampling sites as the TBRG's in order to compare the performances of these instruments. Standard rainfall totalizers are also located at each station to provide a comparable total volume of rainfall for individual events. The data from the TBRG

were collected and stored with a modified 2-channel version of the DAS. Figure 7 shows typical hyetographs of the same thunderstorm obtained with both instruments. The shapes are seen to be similar, and at high rainfall rates the measured intensities are nearly the same. For all rainfall rates the DCPS exhibits superior resolution. Rainfall starting times just about coincide in this example, where the initial rainfall rate is high.

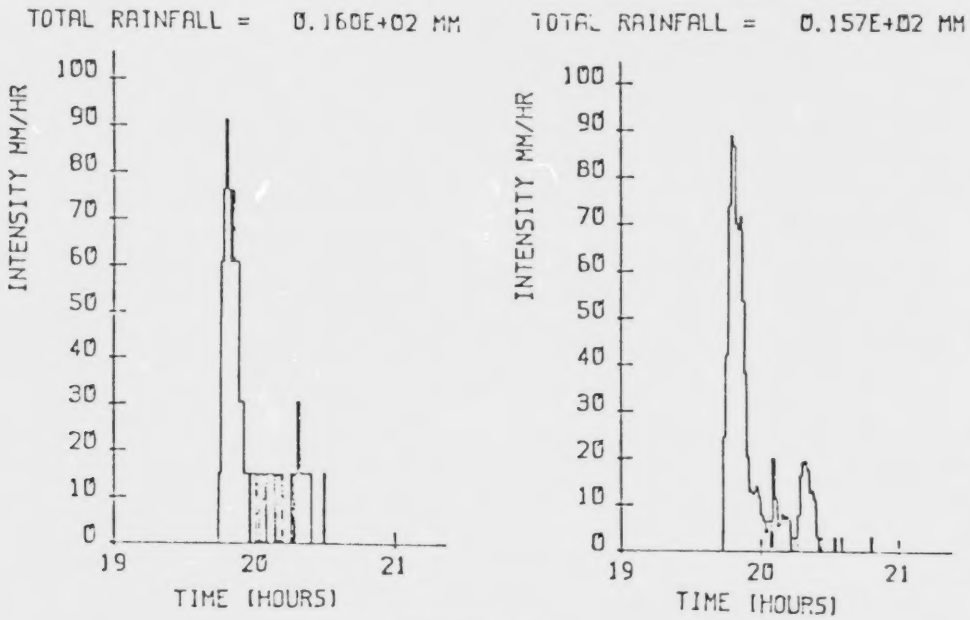

FIGURE 7
Typical hyetographs of the same thunderstorms obtained with both TBRG (Left) and DCPS (Right).

Rainfall instrumentation systems often fall victim to vandals who, all too frequently, destroy the comparatively expensive tipping buckets, no matter how remotely and unobtrusively they may be situated. The small size of the DCPS helps to make it inconspicuous and reduce vandalism problems.

Comparison measurements between the DCPS and the TBRG show that the DCPS is more sensitive, leading to a superior signalling of the beginning and end of rain, and with comparable accuracy. Finally, the versatility of the microcomputer opens the way to a broader range of measures of atmospheric phenomena that share the same electronics and storage/communications.

However, many development problems remain, such as the isolation from the DAS of strong electro-magnetic effects in hostile environments.

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THE SAINT JOHN RIVER FORECAST SYSTEM

By

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THE SAINT JOHN RIVER FORECAST SYSTEM

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ABSTRACT

Following a number of years of flood forecasting on the Saint John River by the Water Resources Branch of the New Brunswick Department of the Environment and the New Brunswick Electric Power Commission with the added support of the Inland Waters Directorate of Environment Canada, the Saint John River Forecast Centre (RFC) was established in its present form in August 1977 with the signing of the Federal/Provincial Agreement Respecting Flood Forecasting.

This paper describes the development and operation of a flood forecast system for the Saint John River Basin. The basic component of the system is the U.S. Army Corps of Engineers' Streamflow Synthesis and Reservoir Regulation (SSARR) model. Other models employed are the Simulated Open Channel Hydraulics (SOCH) model of the Tennessee Valley Authority and the Dynamic Wave Operational (DWOPER) model of the National Weather Service.

The principal means of transmitting real-time data to the RFC are by telephone, teletype, telecopier, data collection platforms, satellites and computer terminals. The data received at the RFC are processed before input to the models. The streamflow data are analyzed and checked for inconsistencies by hand calculations. The real time meteorological data are processed by the Grid Square Areal Meteorological Parameter (GSAMP) program and the meteorological forecast data are processed by a grid interpolation program. The snow course data can be analyzed by either of three different computer techniques to calculate the spatial averages for each sub - basin.

The operation of the forecast models has been facilitated by the development of a computerized procedure. This combined with the three different models (SSARR, SOCH and DWOPER), the data network and the data management procedures constitute the Saint John River Forecast System.

THE SAINT JOHN RIVER FORECAST SYSTEM

INTRODUCTION

Flood forecasting on the Saint John River had been carried out for a number of years primarily by the Water Resources Branch of the New Brunswick Department of the Environment (NBDOE) and the New Brunswick Electric Power Commission (NBEPC). In 1973, a Task Force consisting of representatives of NBDOE, NBEPC and the Inland Waters Directorate of Environment Canada (IWD) was formed to further the development of a flood forecasting system. Further impetus was given to the establishment of a River Forecast Centre by the signing of a Federal/Provincial Flood Forecasting Agreement in August 1977 and by the selection of the Saint John River as a pilot project (1974-1978) under the World Weather Watch (WWW) which is a World Meteorological Organization (WMO) program.

The objective of this Flood Forecasting Agreement is primarily to reduce damages occurring to moveable items in the Saint John River Basin. Activities under the Agreement include establishing, staffing and equipping the Saint John River Forecast Centre (RFC) and designing, developing, calibrating and testing an effective flood forecasting system. The Agreement also provides for the operation of the RFC and the information networks so that the best possible forecast at all times of predicted floods can be achieved.

The RFC functions on a daily basis from mid-March to the end of the spring freshet - usually mid May. During the remainder of the year, forecasts are provided for special

events such as hurricanes, ice jams or other high precipitation events which might cause flooding or a rapid rise in river levels. At times when the Centre isn't producing forecasts for these purposes, a forecast is provided to the NBEPC Energy Control Centre on about a once a week basis. The timing of these forecasts is arranged by consultation between the River Forecast Centre and the Energy Control Centre on Monday of each week, or otherwise as requested to satisfy the needs of the Energy Control Centre.

Permanent accommodations for the RFC are provided by NBDOE. In addition to a number of individual offices, there is a separate sound-proofed communications room and a main work room. A conference room located nearby is used as a briefing room for the press and officials of various private and government agencies whose operations are dependent on the forecast.

Equipment at the RFC include the following:

1) two teletypes capable of intercepting Environment Canada's detailed weather forecasts;
2) a facsimile recorder for receiving weather maps;
3) two high speed computer terminals connected by telephone lines to the Government of New Brunswick Univac mainframe computer in Fredericton;
4) a low speed terminal used to retrieve data from other computers and to access the University IBM 3032 computer as a backup to the Univac System.

5) a high speed printer to retrieve output from the Univac computer;

6) seven telephones for communicating with personnel from the hydro power plants; Emergency Measures Organization (EMO) and Observers, etc.

7) a telecopier for sending forecasts and receiving messages;

8) three code-a-phones for direct access of the latest forecasts by the public and the media.

Under the Flood Forecasting Agreement, a Director was appointed on a part-time basis to manage the River Forecast Centre and a full time forecast technicial was engaged. A hydrologic engineer (full-time) and two meteorological technicians (part-time) were provided by NBDOE. The RFC staff is augmented on a continuing basis during the spring runoff period and at other times as required by staff from IWD and NBEPC. This provides the necessary backup and makes occasional round-the-clock operation possible.

DEVELOPMENT OF FORECASTING MODELS

Saint John River Basin

The Saint John River Basin covers an area of 55,000 sq. km. of which about 51% is in the Province of New Brunswick 13% is in the Province of Quebec and 36% in the State of Maine. The NBEPC owns and operates four hydro generation plants and their associated headponds in the Saint John River Basin, namely, Grand Falls, Beechwood, Tobique and Mactaquac. The Maine Public Service owns and operates the hydro generation plant at Tinker. The locations are shown on Figure 1.

The Saint John River is characterized by extreme variation in flow, where minimum flows can be as low as 85 m^3/s while high flows can be in excess of 11,330 m^3/s. It is also characterized by a relatively steep gradient which results in reasonably short lag times. A flood crest could travel the entire 430 km course of the river to Mactaquac Dam in less than 24 hours. The principal areas of floods in the Saint John River Basin are shown on Figure 1.

The hydraulic characteristics of the lower Saint John River from just below the Mactaquac Dam to Saint John are unique. The narrow gorge at the mouth of the river, know as the Reversing Falls, together with large tidal fluctuations in the Bay of Fundy combine to restrict river outflow especially during high flow periods, thus causing a storage of water upstream over a period of time. The flooding characteristics of the area are further complicated by flow transfers between the main river and large storage areas

adjacent to the river. As flood waters are backed up by the Reversing Falls, they are stored in the main channel and associated flood plain lands of the lower Saint John River as well as in Kennebecasis Bay, Washademoak Lake, Belleisle Bay, the Grand Lake System, and the Oromocto River Valley.

Model Selection

Prior to 1972, there were individual effort by NBDOE and NBEPC to forecast spring high flows and stages along the Saint John River using simplistic flood forecasting methods. Towards the end of 1972, these two Provincial agencies joined together in a search for available operational forecasting computer programs. As a result, the Streamflow Synthesis and Reservoir Regulation Model known as SSARR (U.S. Army, 1972) was chosen as the best available computer model at that time to be utilized for flood forecasting in the Saint John River. The SSARR model was developed by the North Pacific Division of the U.S. Army Corps of Engineers.

The SSARR model was obtained in early February 1973 and the task force consisting of NBDOE, NBEPC and IWD staff was formed to adapt the model for application to the Saint John River Basin. After minimal calibration, the model was operational for flood forecasting by the end of March 1973. Figure 2 shows a comparison of actual and forecasted streamflow, precipitation, and temperature for the Saint John River Basin, as well as a comparison of flows below the Mactaquac Dam. This figure

indicates that the accuracy of 1973 streamflow forecasts are significantly dependent on the accuracy of weather forecasts.

In mid-1973 NBDOE requested IWD to extend the forecasting system to the lower reach of the Saint John River in order to forecast water levels at Fredericton and Maugerville. IWD agreed and used the SSARR program as it also has the ability to route river flows as a function of multivariable relationships involving the backwater effects from tides.

In 1979 the dynamic wave operational model (DWOPER) was utilized for the purposes of developing flood risk maps for the land along the River from Fredericton to Lower Jemseg. (MacLaren Atlantic Ltd. 1979). An operational forecasting version of this model has been transferred to the RFC. By 1980 the DWOPER model was fully incorporated into the Flood Forecasting system and was run in parallel with the SSARR model. Around the same time, NBEPC also acquired the dynamic routing model from the Tennessee Valley Authority (TVA). This dynamic model known as the Simulation of Open Channel Hydraulics (SOCH) was used to modify the old operating rule curve of the Mactaquac hydro power plant and to improve the forecasts of releases to the Saint John River downstream of the Mactaquac Dam.

Model Schematic and Calibration

The SSARR model is a conceptual mathematical hydrologic model which synthesizes streamflow by evaluating snowmelt and rainfall runoff. After considering all factors including

the locations at which forecasts were required, the locations of existing streamflow gauges and the physiographic features of the remaining ungauged areas, the Saint John River Basin was divided into 66 sub-basins as shown on Figure 3.

The snowmelt and rainfall-runoff relationships were established for the 29 sub-basins which have hydrometric stations at their outlets by calibrating six events. Three fall events (1969, 1973, 1976) were first employed to calibrate the model parameters excluding the complicating factor of snow. Following this, three spring rainfall/snowmelt events (1972, 1973, 1974) were used to complete the calibration.

The meteorological data used to calibrate the sub-basin were taken from the Atmospheric Environment Service (AES) publication and were first processed through the Grid Square Areal Meteorological Parameter Program known as GSAMP.

This GSAMP program was developed by Dr.N Trivett of AES and was utilized to distribute station daily values of mean temperature and precipitation so that an areal average for each sub-basin could be computed.

There were 657 grids containing the Saint John River Basin and each 10 km square grid was assigned to one of 66 sub-basins used in the SSARR model. Only the area of the grid inside the sub-basin would be assigned to that sub-basin as these area weightings were used to determine the average precipitation and temperature over the sub-basin. Physiographic parameters such as average grid

elevation, slope and azimuth etc., were calculated for a 10 km square grid centered on the climatological stations. The climatic normals of temperature and precipitation were first regressed against their respective station physiographic parameters using a step-wise multiple linear regression program. Climatic normals of precipitation and temperature for each grid in the system were then determined from these regression equations and the respective grid physiographic data. The normal ratio method was used to obtain daily values for each grid from surrounding station data weighted by the inverse square of the stations' distance from the grid. The areal average value for each sub-basin was then obtained by summing each daily grid value weighted by the area of the grid in the sub-basin.

The daily amounts of precipitation, input into the SSARR model, were distributed over eight three-hour periods. The percentage of the total precipitation which occurred during each three-hour period was determined by analyzing hourly precipitation data for selected climatological stations.

Snowpack water equivalents for the start of the melt season were determined based on hand-produced iso-line maps using data from roughly 70 snow courses while potential evapotranspiration losses were estimated from long term mean monthly lake evaporation data.

The hydrometric data were provided by Water Survey of Canada (WSC), United States Geological Survey (USGS) and Quebéc Ministere des Richesses Naturelles. Three-hourly

streamflow data were used to calibrate the sub-basins.

In order to determine the adequacy of the calibration for each sub-basin, several accuracy criteria were adopted (IWD 1979). It was decided that the primary criterion would be a weighted coefficient based on the Nash criterion (C_n); the Pointe criterion (C_p) and the criterion of volume (C_v). This composite criterion (C_f) also known as the criteria of precision, was originally used on the Ottawa River (Rousseau et al 1976). It is defined in terms of the C_n, C_v and C_p criteria as:

$$C_f = (1 - C_n) + 2C_p + C_v$$

The criteria of Nash measures the general quality of the runoff model calibration for the whole data period with equal weight assigned to high and low river discharges. For a perfect reproduction, C_n yields a value of 1. The value of C_n decreases with the quality of calibration. A low value indicates that the response of the model to precipitation and melting snow is not well reproduced in general.

The criteria of Pointe measures the quality of the runoff model calibration that uses a proportional weighting that increases with the value of flood discharges. For a perfect hydrograph reproduction, C_p yields a value of 0, and C_p increases when the calibration quality diminishes. If it is high, that indicates the shape of the flood hydrograph peak is not well reproduced. The criteria of volume measures the quality of the reproduction of the water balance comparing modelled and actual

hydrographs. For a perfect reproduction, C_v yields a value of O, C_v increases when the quality of calibration diminishes.

On the basis of some sensitivity tests(IWD 1979) using controlled variations to an assumed hydrograph, it was suggested that the standards for the calibration of a sub-basin watershed model be as presented in Table 1. It was agreed that the composite value C_f should not exceed 1.25.

TABLE 1

SUGGESTED ACCURACY STANDARDS
FOR THE CALIBRATION OF A SUB-BASIN
WATERSHED MODEL

Criterion	C_n	C_p	C_v	C_f
Perfect	1.00	0.00	0.00	0.00
Objective	0.90	0.20	0.02	0.50
Acceptable (upper limit)	0.80	0.50	0.05	1.25

Of the eleven sub-basins which were calibrated for all six events, only two had C_f values less than 1.25 for all 6 events, eleven had C_f values less than 1.75 for three or more events and one sub-basin had C_f values greater than 1.25 for all six events (Tang et al 1980b).

After the calibration was complete, a verification exercise based on the 1979 spring event was carried out (Tang, 1980a). This test which employed both the old and the newly calibrated models and recorded climatological data clearly indicated the improvement of the newly calibrated model. Examples of the hydrographs produced by both models are

provided in Figure 4 along with the recorded hydrographs and computed values for the accuracy criteria.

The channel routing component used in the SSARR model was reviewed and recalibrated by NBEPC (Hudson 1979). The 0700 hour flow readings for the 1979 forecast season were used in the calibration. The model was then verified using the 1973 and 1977 average daily flows. The results of the verification indicated that the model gave satisfactory results. The schematic of the SSARR model for the Saint John River Basin is shown on Figure 5.

The backwater mode of the SSARR model as applied to the lower Saint John River was calibrated in 1973 based on data from the 1971 and 1973 floods. The main channel shown in Figure 6 was divided into nine sub-reaches and the off-channel storages, located north of the Trans Canada Highway between Fredericton and Jemseg, were divided into four sub-reaches. Control stations were established at the base of the Mactaquac Dam, between the sub-reaches and at the Reversing Falls. Each of the sub-reaches were provided with a storage relationship and one or more backwater relationships. The stage-storage relationships were determined for each segment using aerial photography and hydrometric measurements of historical events. The backwater relationships were determined by a trial and error procedure employing streamflow data and water level data. A general accuracy criterion of 0.15 m deviation from the recorded stage hydrographs for Fredericton and Maugerville

was employed in the calibration procedure.

The DWOPER model for the Lower Saint John River was calibrated using data from the 1973 - 1974 and 1977 flow events. (MacLaren Atlantic Ltd. 1979). A general schematic illustrating the system's main components as modelled is presented on Figure 7.

The river system is described by specifying arrays of cross-sections. The flow and storage characteristics of each element reach are defined by a function of the average shape and hydraulic characteristics associated with the boundary cross-sections. Lateral off-line storage for the elemental reach is specified as an extension of the cross-section. The segment from Fredericton to Lower Jemseg is hydraulically the most complex area along the reach. The off-line storages are accounted for including the effects of the Trans Canada Highway on flow exchange to and from the Portobello Stream - Grand Lake storage area. The section of the Trans Canada Highway from Maugerville to Lower Jemseg acts as a flow bifurcation weir, with the amount of flow exchange depending on the water level calculated at each time step for each cross section connecting the main channel and tributary. Flow transfer to the Grand Lake storage is therefore simulated in the model either via the Jemseg River or by over-flow across the Trans Canada Highway to Portobello Stream and hence to Grand Lake or by a combination of both mechanisms.

The reach from Lower Jemseg to Indiantown accounts for off-line storage affects in the Washademoak Lake, Belleisle Bay, Long Reach and Kennebecasis Bay areas as indicated on Figure 7.

The reach from Indiantown to Pugsley Wharf incorporates the influence of the Reversing Falls and channel constriction effects in this area and thus allows input of time varying tidal conditions at Pugsley Wharf. It was found necessary to adopt a two-hour computational time step in order to adequately simulate the effects of the tide.

The Manning roughness coefficient (n) is the main calibration parameter. Values for n were determined with the aid of the model's automatic calibration feature as well as by trial and error simulations.

In a test based on the 1979 event, one of the most severe flood events on record, the DWOPER version was compared to the SSARR version. Both versions performed equally well in simulating water levels for upstream locations such as Fredericton However, SSARR performed poorly for downstream locations because it was calibrated only for Fredericton and Maugerville.

Table 2 compares the simulated water levels at Fredericton and Oak Point produced by each model to the actual instantaneous water levels.

The SOCH model was acquired and adapted for application to the Mactaquac headpond by NBEPC. The model was calibrated utilizing 1973 and 1974 historic records (Ismail et al 1983). There was good agreement between the actual and calculated water levels along the river reach between the Mactaquac Dam and Beechwood tailrace. Calculated discharges at the dam were also in close agreement with those recorded at McKinley Ferry 4.4 km downstream of the dam.

TABLE 2 COMPARISON OF WATER LEVELS SIMULATED USING THE SSARR AND DWOPER MODELS (April 25-May 5, 1979)

Date (0700 hr)	Stage at Fredericton (metres)			Stage at Oak Point (metres)		
	SSARR	DWOPER	ACTUAL	SSARR	DWOPER	ACTUAL
April 25	4.44	4.28	4.52	2.61	2.45	2.59
April 26	4.69	4.39	4.83	2.64	2.44	2.73
April 27	4.96	4.75	5.25	2.70	2.55	2.91
April 28	5.58	5.64	6.03	2.79	2.72	3.11
April 29	6.51	6.56	6.77	2.89	2.93	3.38
April 30	7.55	7.64	7.83	3.01	3.36	3.79
May 1	7.97	7.76	7.86	3.36	3.88	4.06
May 2	7.68	7.49	7.74	3.61	4.52	4.46
May 3	6.87	6.79	6.99	3.85	4.83	4.70
May 4	6.42	6.24	6.63	3.95	4.70	4.72
May 5	5.91	5.65	6.24	3.91	4.33	4.60
Peak	8.00	7.93	8.05	3.96	4.81	4.73

One of the objectives of utilizing the SOCH model was to improve the understanding of the dynamic characteristics of the Mactaquac headpond so that the operation of the headpond could be efficiently managed.

The Mactaquac headpond is somewhat unique from an operational point of view, since there are constraints at the upper end of the headpond at the town of Woodstock, 80 km upstream as well as below the dam in the Fredericton/Maugerville area.

The SOCH model requires the inflows to the headpond and the water level at Mactaquac as input parameters. Other inputs include geometric and hydraulic characteristics of the channel cross sections, roughness coefficient curves, the operating rule curve and the initial discharges and stages at each cross section.

REAL-TIME DATA COLLECTION AND PROCESSING

Streamflow Data

There are 33 telemarks, one Device for Automatic Remote Data Collection (DARDC) unit and six Data Collection Platforms (DCP's) to provide information on river levels. Of the six DCP's one is capable of providing both the river levels and the precipitation data. The stream gauging locations and relay system are shown on Figure 8.

Observations of river stage, reservoir level, storage change and flow regulation are obtained by the RFC with assistance from NBEPC at Grand Falls and at Mactaquac. Most of the locations supplying real-time data are equipped with telemarks which can be dialed up with a telephone. The data relayed from the DCP's are converted to a radio signal which is broadcast every three or six hours to the Geostationary Operational Environmental Satellite (GOES) and then transmitted to the World Weather Watch (WWW) Building in Suitland, Maryland. A Silent 700 terminal at the RFC is used to retrieve the DCP data file from the computer at the WWW Building. It is also used to poll data from the DARDC unit at Fort Kent.

Once the information is obtained it is entered into a master log and the readings of river stage are converted to flows using rating tables.

During the winter when the rivers and streams are ice-covered, gauge readings at hydrometric stations cannot be converted to flow using the standard open water rating curves. This is because of the backwater effect created by the ice-cover. At these times

estimates of actual flow at ice-covered locations are made by relating a few known flow values to the sites affected by ice. These values are determined in various ways. For example, flow at several gauging stations are metered through the ice periodically throughout the winter to give true values of discharge. Hydroelectric plant discharge values also serve as a guide. In addition, there are a few stations in the Basin located on stretches of river which normally do not freeze over and they provide true flow values for use in calculating actual flows at ice covered sites.

When the collection of flow information has been completed, a check on the consistency of the data is carried out by hand. Observed flow values are compared with those computed at the four summing points used in the model - Fort Kent, Grand Falls, Bristol, and Mactaquac. This comparison is performed using the same logic progression as programmed in the SSARR model. Approximations are used for the various routing times between summing points on the main stream and major tributaries. By means of this calculation, the RFC staff is able to make a comprehensive analysis of the flow conditions in the entire Basin. Inconsistencies in the data, resulting from such things as malfunction of equipment or mistaken interpretation of signal, can be identified and corrected at this time. The corrected flow data are then keyed into the computer together with any update parameters that are required to adjust the watershed initial condition. The parameters used to update the model are Soil Moisture Index (SMI) Baseflow Infiltration Index (BII), Snow Covered Areas (SCA). Melt

Rate (MR) Accumulated Runoff (AR) and Total Seasonal Runoff (SR). The keyed-in data are then processed and arranged into the required format.

Snow Data

The snow covered area in the basin is derived on an experimental basis from three agencies who use a variety of procedures to analyze the satellite imagery. These agencies are National Environmental Satellite Service (NESS) in Washington, AES in Toronto and a local contractor. Maps showing snow covered area are transmitted to the RFC by telecopier, and hand delivered by the local contractor, beginning with the onset of the spring snowmelt season. These maps are compiled whenever cloud cover permits observation of a major portion of the basin-usually once a week.

Since 1975, a cooperative snow survey program has been scheduled by the Eastern Snow Conference and the surveys are usually scheduled monthly during January and February and biweekly from March until the snow pack is fully depleted. There are nine agencies involved and the RFC compiles and distributes by mail final tabulation and maps to all interested parties. Snow course locations and relay systems are shown on Figure 9.

After each snow survey is complete and upon receipt of the snow survey results at the RFC, the snow depth and water equivalent data were keyed into the computer for further processing. The snow courses are classified according to cover type (forest open and mix).

A computer program which was developed by AES (Trivett et al 1980) was used to calculate the spatial averages for each sub-basin and to map the snow course data. Three techniques

which include trend surface analysis, proximity analysis and multiple regression analysis can be used to process the snow course data.

Trend surface analysis assumes that the value of the mapped variable at a point in space can be segregated into a regional component and a residual component. The regional component results from large scale processes whereas the residual component is presumed to result from local factors affecting the variable being analyzed. The form of the trend surface used is a second degree polynomial involving x and y coordinates.

In the proximity analysis, the snow water equivalent for each grid cell is calculated as the average of the nearby snow courses weighted by the inverse of the distance of the snow course from the grid cell.

In the multiple regression analysis, the effect of elevation on the spatial distribution of snow course data is examined by including it as an independent variable available for selection by the step-wise multiple regression program. Estimates of snow water equivalent for each grid cell are calculated using the x and y coordinates of the grid cell and its average elevation.

In addition to distributing the point snow course data over space by one of the previously described techniques, it is necessary to calculate sub-basin averages of snow water equivalent. The snow water equivalent for each grid cell can be mapped separately by cover type using gridded data from any of the three techniques mentioned above. A weighted average

snow water equivalent value for each cell is calculated using the area of each cover type in the cell. Each grid, or a percentage thereof, is assigned to a sub-basin in order to calculate the sub-basin averages of the distributed snow course data. A composite map of the weighted grid cell data is printed along with the sub-basin averages of snow water equivalent and its corresponding volume.

Another computer program is used to calculate the long term averages (referred to as normals) of snow water equivalent, snow depth and snow density. The snow course data as a percentage of the "normal" and the mean snow water equivalent for the upper and lower Saint John River Basin are also calculated. Finally, iso-line maps of snow water equivalent and the percent of "normal" snow water equivalent are prepared.

Real-Time Meteorological Data

Meteorological parameters are observed, recorded and transmitted in real-time by government agencies, private companies, hired observers and by DCP's via the GOES satellite. There are about sixty weather observers reporting in the Saint John River Basin and six DCP's to provide information on precipitation. Of the six DCP's one is capable of providing both the river levels and the precipitation data. Locations of these meteorological stations and the relay system are shown on Figure 10.

Meteorological data from Canadian and the United States' principal stations are received by teletype connected to meteorological telecommunication circuits of the national

meteorological agencies (AES and NWS). Also a special bulletin consisting of hydrometeorological data collected and transmitted by the Portland NWS office has been added to the messages received by the RFC on the regional meteorological circuits.

Upon receipt of the real-time meteorological data, the values are recorded on a master log and plotted on maps. When the collection of the data is complete, an isohyetal map of precipitation and an isothermal map of the mean temperatures are drawn. The data are also keyed into the computer to be processed by the GSAMP program which has been discussed in the previous section. The special output from the GSAMP program is a computer file which contains the areal average of temperature and precipitation for each sub-basin, arranged in the format required by the SSARR model.

Meteorological Forecast

The system for providing meteorological forecasts to the RFC utilizes 12 grid points organized in a rectangular pattern (grid length 190 km) centered over the Saint John River Basin. Precipitation parameters and mean temperature anomalies for each grid point are produced using numerical models at the Canadian Meteorological Centre (CMC). They are transmitted to the Maritime Weather Office (MWO) in Bedford, Nova Scotia via teletype and are stored on a computer disc file at the MWO. A Texas Instrument Silent 700 computer terminal and telephone link are used to access the meteorological forecasts from the computer file at the MWO and to transfer it to the Univac computer.

An example of the meteorological forecast file is shown in Figure 11.

After the meteorological forecast file has been transferred to the Univac computer, the grid point data are processed by a grid interpolation program developed by AES, Scientific Services Unit, Fredericton. This program calculates forecast precipitation amounts and forecast mean daily temperatures at each basin centroid. The technique employs straight line interpolation between the grid points and the temperature anomaly forecasts are converted to mean daily temperature by adding the normal temperature for each location on that day.

The daily temperature used in the model is to determine the total daily snowmelt. The melt distribution for each day is specified for eight three-hour periods in the input file.

The resulting forecast data is written to a file in a format suitable for input to the SSARR model. This output is then merged with the real-time data, in the required sequence and can then be input directly into the SSARR model.

OPERATIONAL PROCEDURE

At the RFC, the operation of the forecast models has been simplified and facilitated by the development of a computerized procedure. All the modelling programs are combined together as components of the forecasting system. The system is structured in such a way that it is easy to use (user friendly). All the data preparation programs are interactive. The organization chart of the system is shown on Figure 12.

In order to avoid any delay of producing the forecast due to the failure of the Univac Computer, a duplicate of the forecasting system has been installed on the IBM computer. Each data file produced on the Univac computer is being backed up on IBM computer instantly.

Since 1980, the Mactaquac headpond has been regulated from the River Control Centre (RCC) located in the Mactaquac plant by using the SOCH model. Both the RFC and the RCC use the New Brunswick Government Sperry Univac computer system, and the IBM computer at the University of New Brunswick as the backup system. The computing facilities at the RFC and its link between the RCC and the backup system are shown on Figure 13.

As time is critical during the flood forecasting operation, each task is streamlined in order to produce the forecast in a timely fashion. The critical path of the operation schedule is shown on Figure 14.

The output of the SSARR model constitutes the flow forecast for the next five days for 32 locations within the Saint John River Basin. Flows forecast for the eleven tributaries of the

Saint John River between the Mactaquac Dam and the Beechwood tailrace are isolated and written on a separate computer file. These forecast flows in conjunction with the water level at Mactaquac, obtained from the operating rule curve, constitute input parameters to the SOCH model.

The output of a SOCH run is the calculated water level and discharge for each cross section along the headpond at time intervals of one minute for a five day period. Planned discharges at the Mactaquac Dam, based on the SOCH model are passed on to the River Forecast Center and fed into the water level routine of the SSARR and/or the DWOPER model to obtain water level forecasts for downstream of the Mactaquac Dam. The Flow Chart for the RCC spring operation is shown on Figure 15.

The five day flow forecast produced by the SSARR model at 0700 hours daily for eight locations along the river are issued each day before noon by telecopier to NBEPC, EMO, IWD, AES and by telephone to NWS at Portland.

After the flows at Mactaquac Dam exceed 2266 m^3/s, the five day river stage forecasts @0700 hour obtained from the DWOPER are also issued daily before noon to the above agencies and three day forecast are provided to the New Brunswick Information Service (NBIS) for distribution to the media and the public. When the situation warrants it, forecasts and warnings are provided to the public by the use of taped messages accessed by telephone and verbally through radio and T.V. stations.

The frequency of runs and forecasts varies depneding on the river situation and as many as three a day may be issued under extreme flood conditions.

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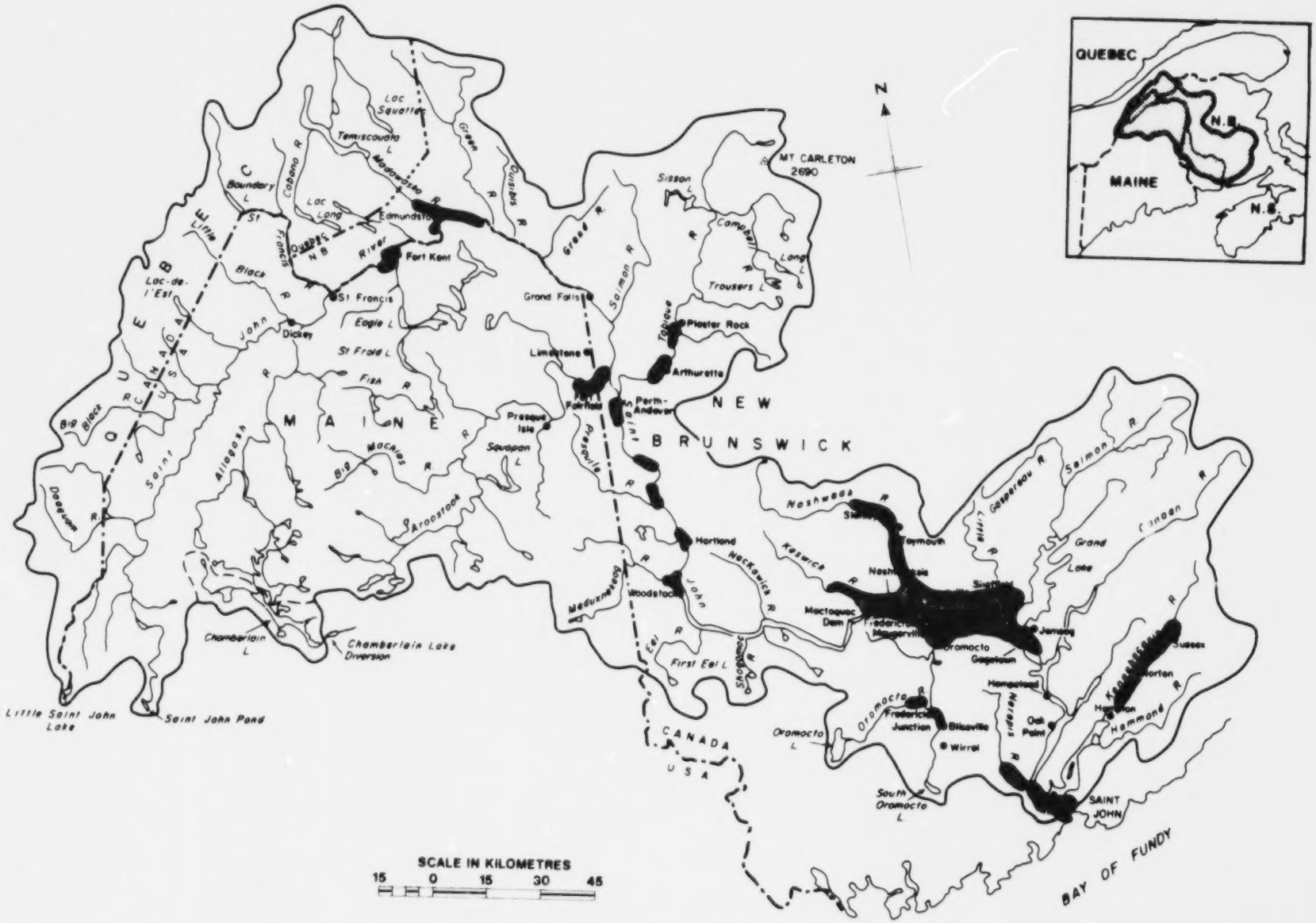


Fig. 1. Flood Damage Areas – Saint John River Basin (IWD 1973).

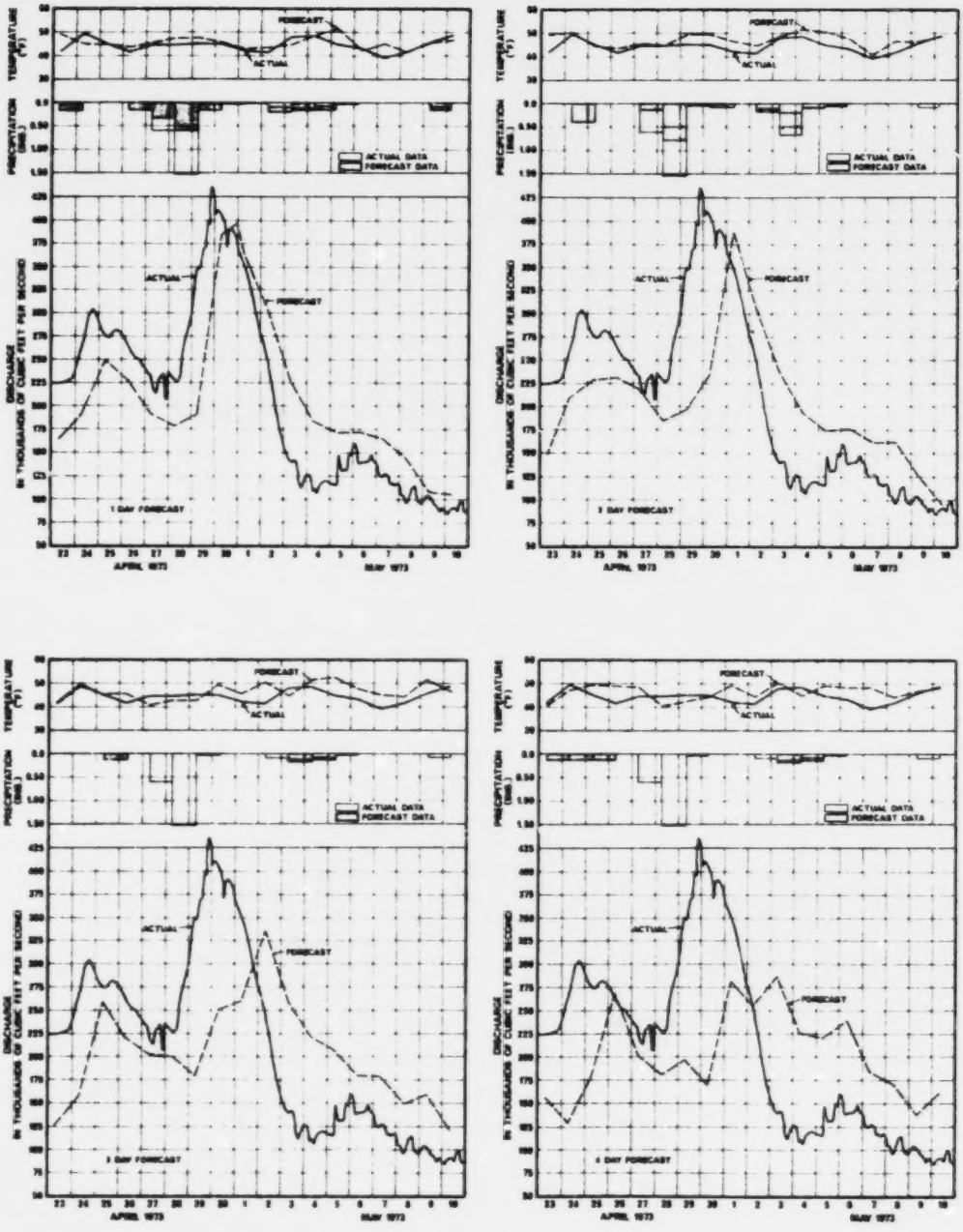


Fig. 2. Comparison of Actual and Forecast Streamflow, Precipitation and Temperature – Saint John River below Mactaquac Dam (IWD 1974).

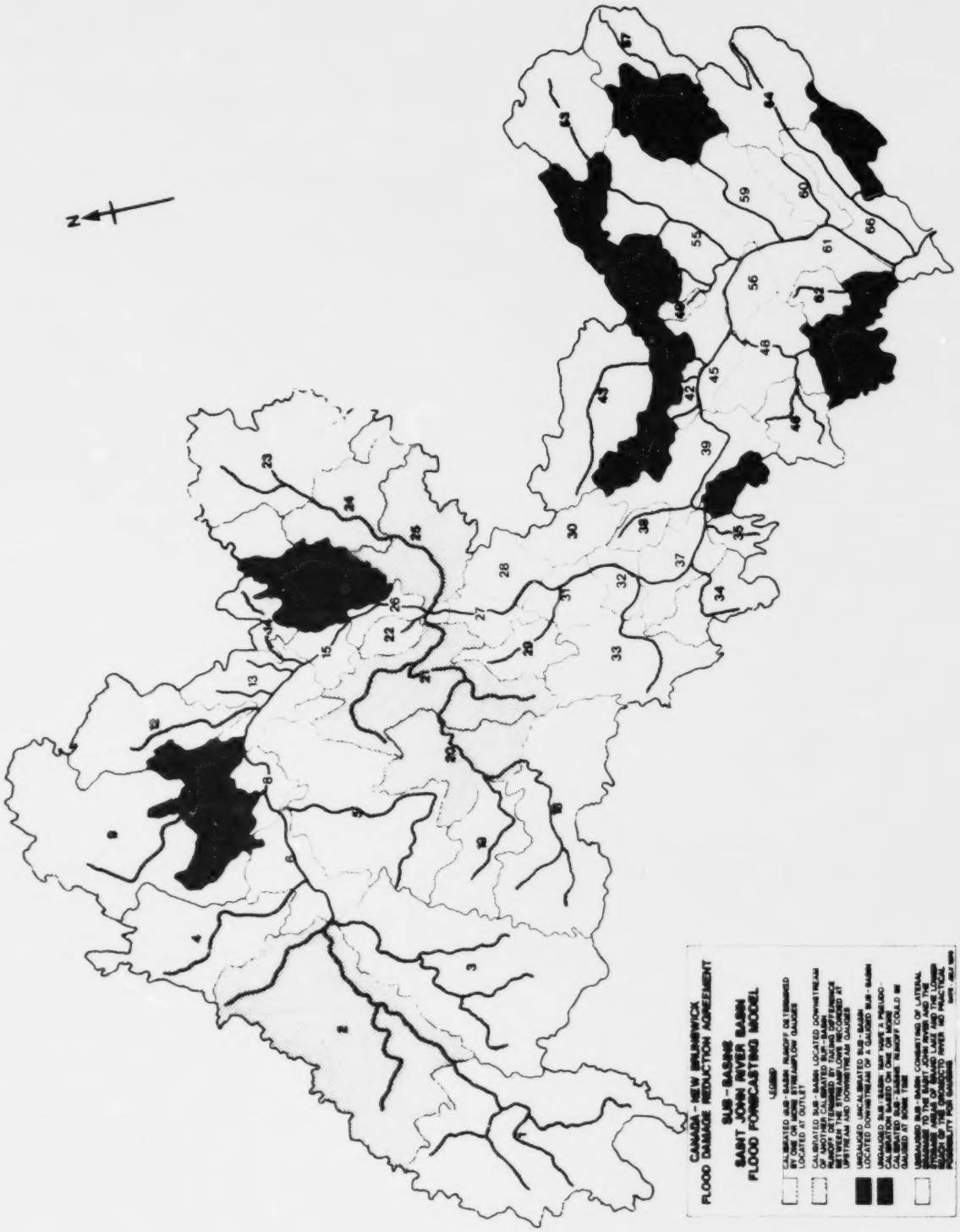


Fig. 3 . Sub-Basins Saint John River Basin Flood Forecasting Model.

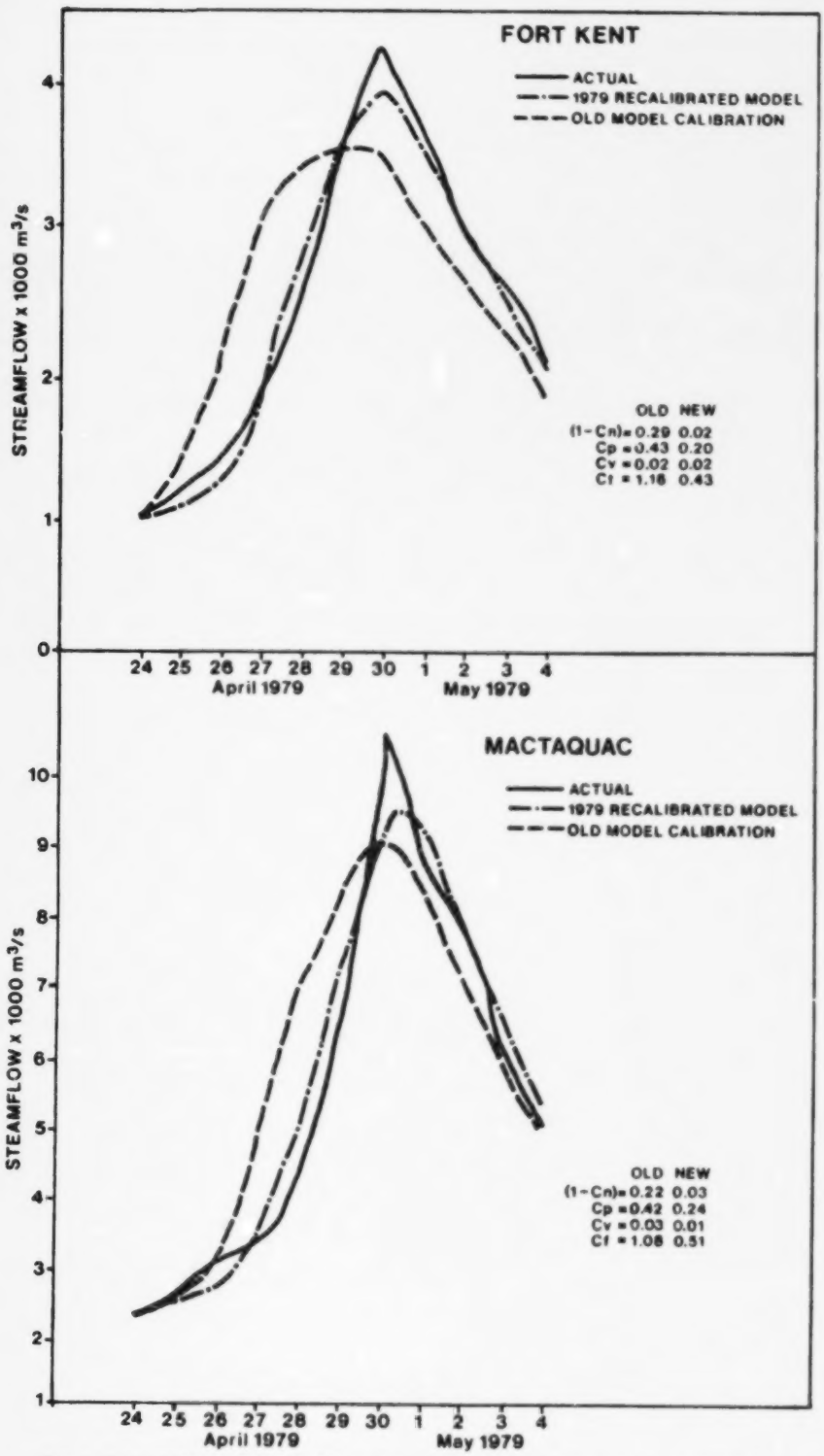


Fig. 4. Comparison of Old and New Forecast Models Based on Simulation of the 1979 Spring Flood Event (Tang et al 1980a).

Fig. 5. Flow Chart – Saint John River Basin Flood Forecasting Model.

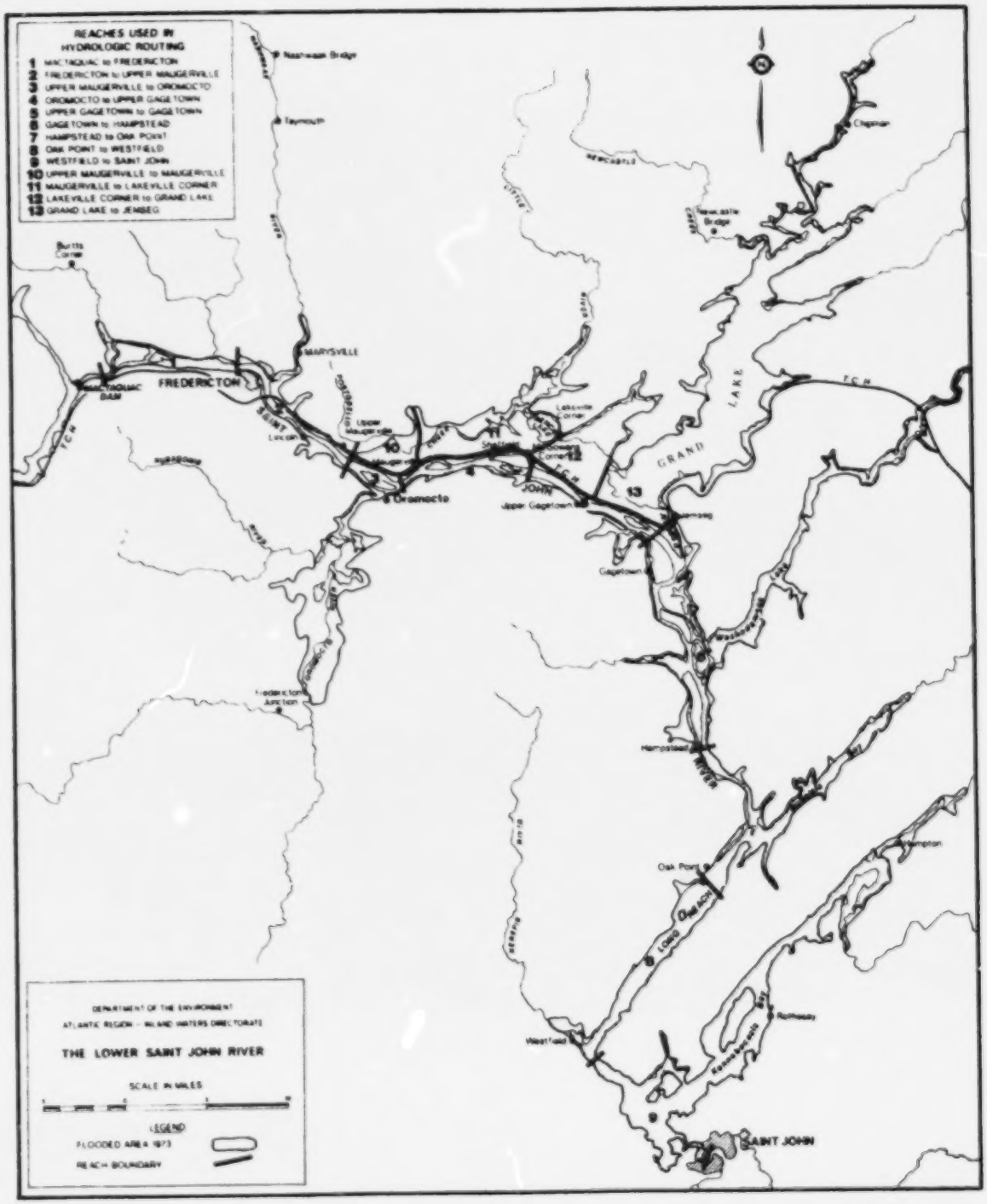
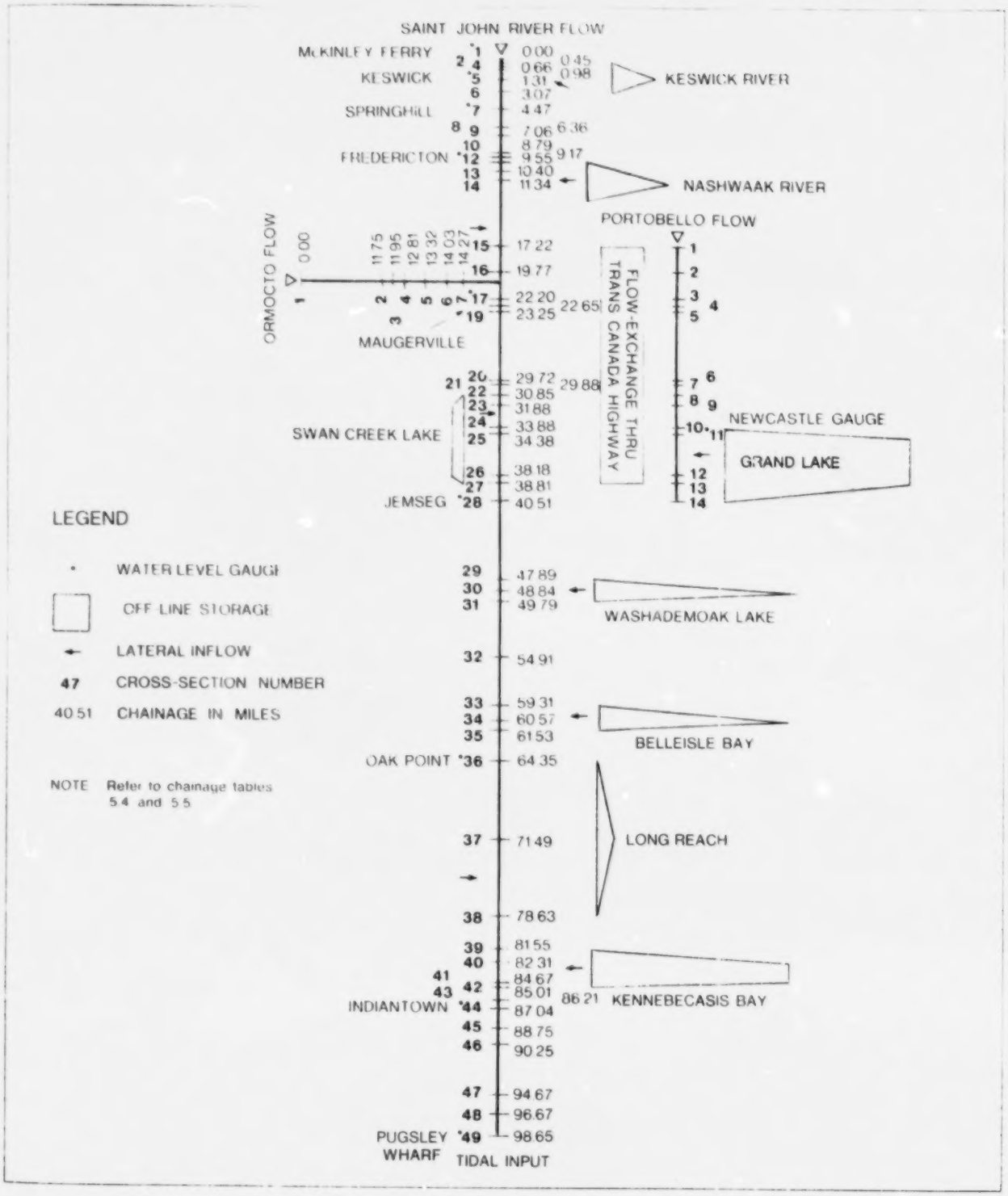


Fig. 6. Reaches Used in Hydrologic Routing on the Saint John River downstream of the Mactaquac Dam (IWD 1974).

SCHEMATIC OF DWOPER MODEL OF THE LOWER SAINT JOHN RIVER

Figure 7



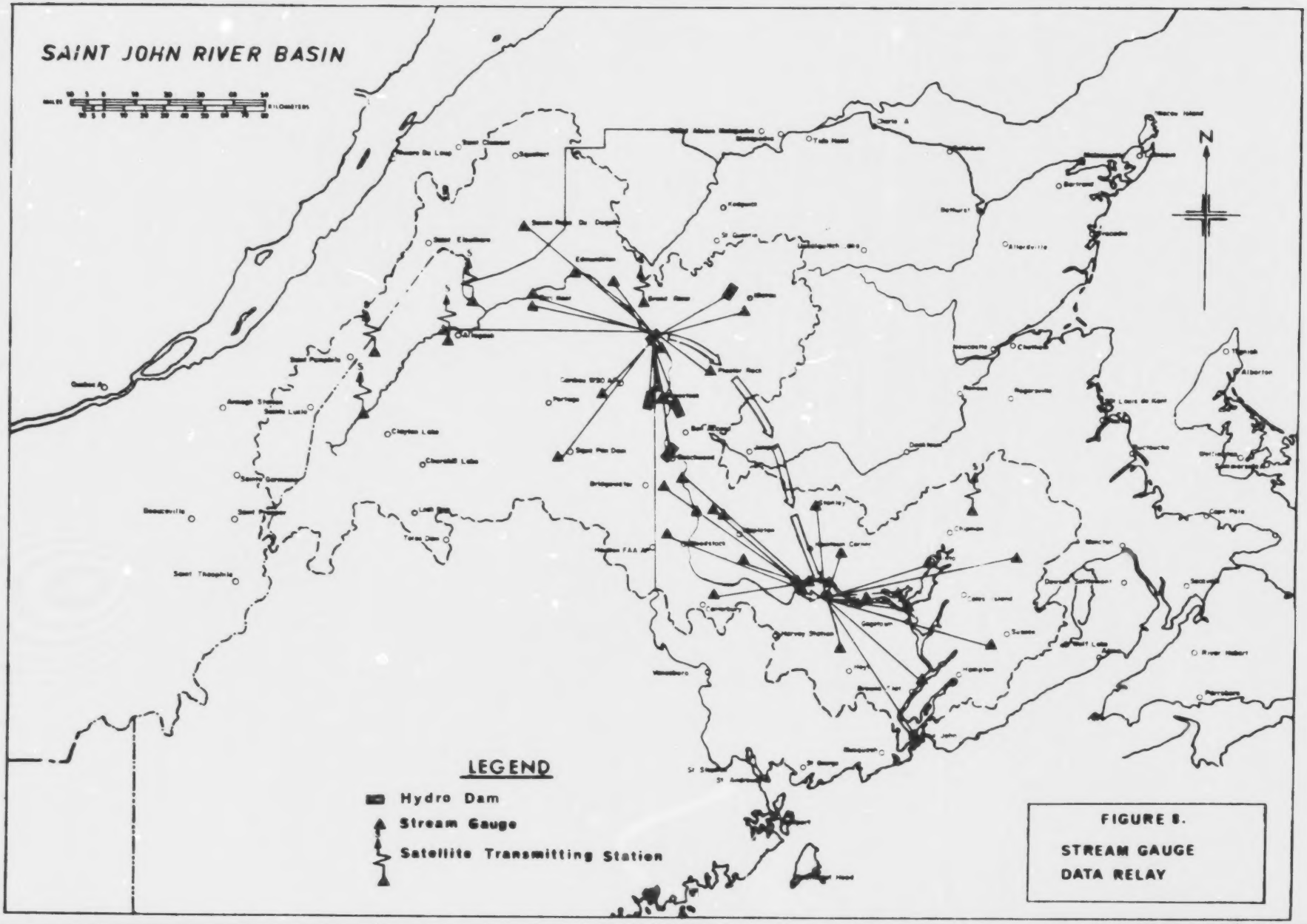


FIGURE 8.
STREAM GAUGE
DATA RELAY

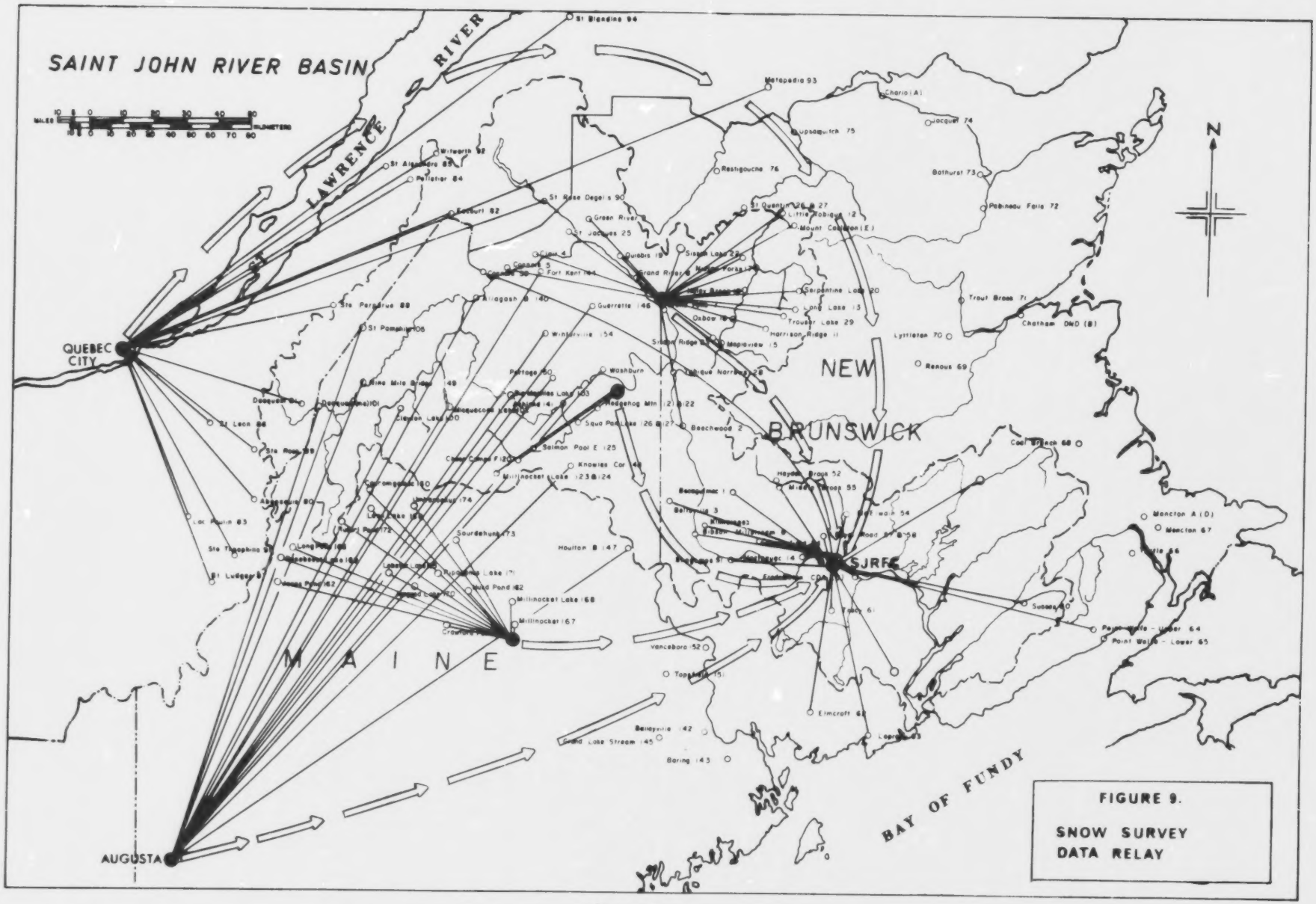


FIGURE 9.

SNOW SURVEY
DATA RELAY

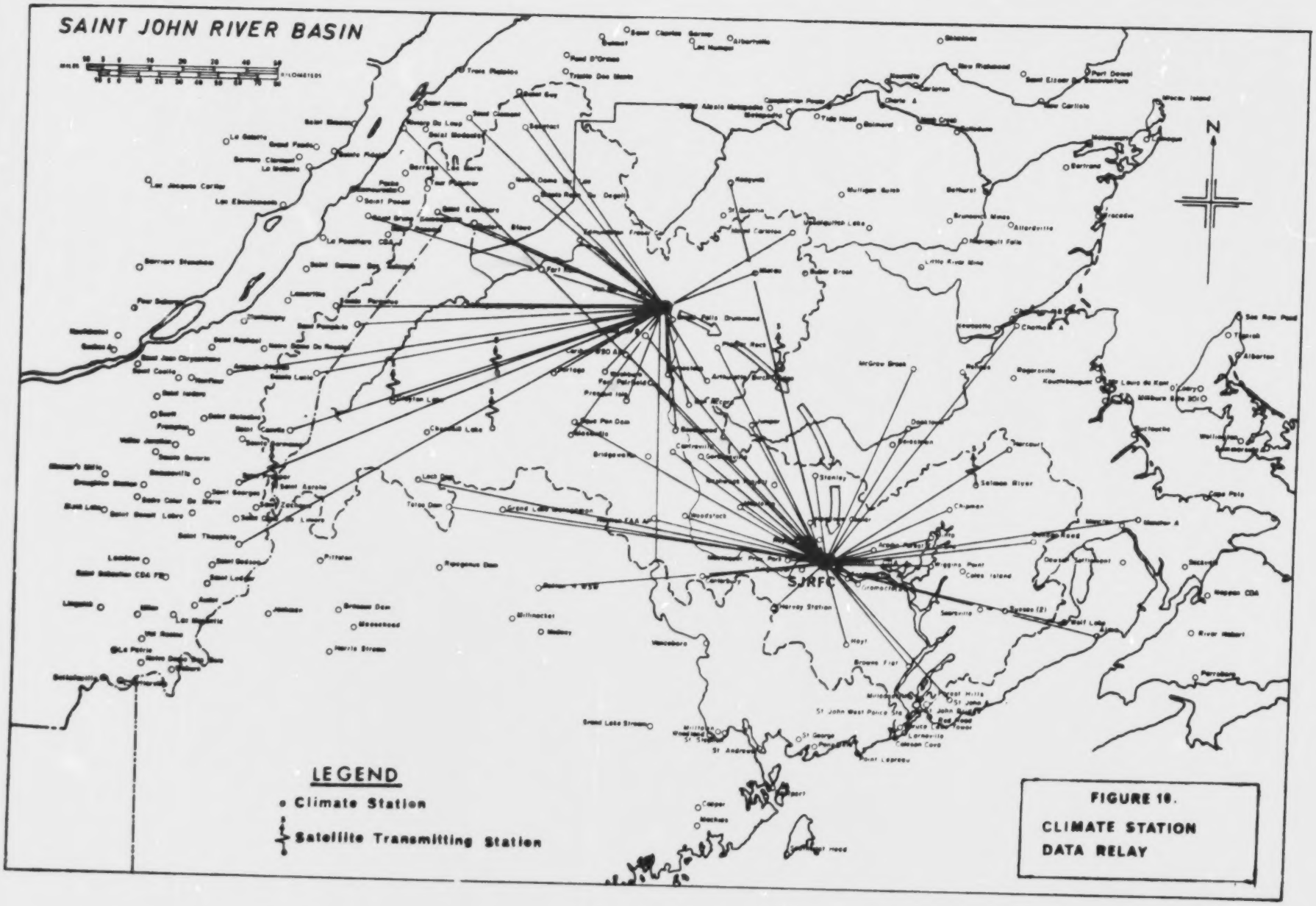


FIGURE 10.
CLIMATE STATION
DATA RELAY

Figure 11. Interpreting Meteorological Forecast File

```
AEICOM HFX

SIGN ON CODE
NRSJREF

FLOOD FORECAST MESSAGE-GRID POINT DATA  10/30/11/1981
  1   0   0   0   1   0   0   0   2   2   1   0
  1   0   0   0   1   0   0   0   2   2   1   0
  0   0   0   0   0   0   0   0   0   0   0   0
  0   0   0   0   0   0   0   0   0   0   0   0
  0   0   0   0   0   0   0   0   0   0   0   0
  0   0   0   0   0   0   0   0   0   0   0   0
 -2  -4  -4  -4  -1  -2  -3  -4   0  -1  -1  -1
  4   2   2   2   4   3   2   2   5   3   3   3
  4   4   3   3   5   4   3   3   6   4   4   4
  1   1   0   1   2   2   2   1   3   4   3   3
 -1   0  -1   0   0   2   2   0   2   4   3   2
  6   6   6   5   6   6   4   4   7   6   5   4
 10   7   6   6   9   8   6   6   8   9   8   6
  9   3   1   1   6   5   1   1   4   6   4   1
 11   3   0   0   8   6   0   0   6   4   1   0
```

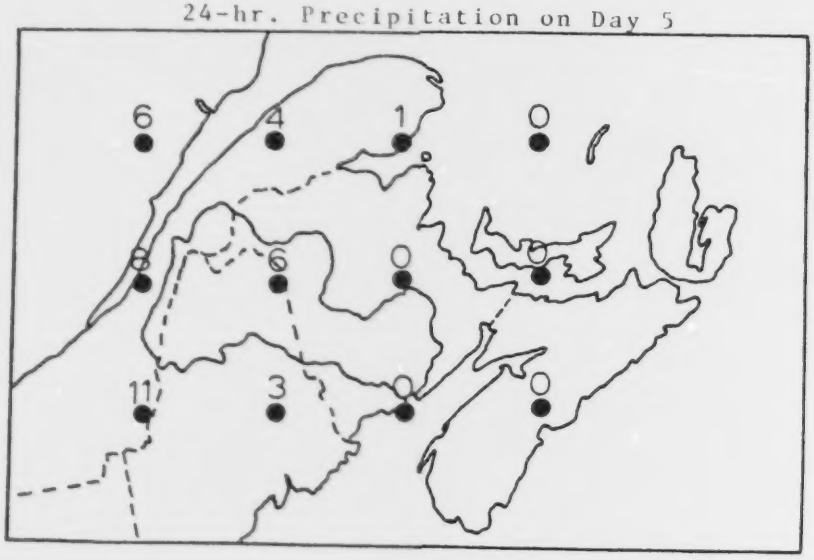
6 6-hr Precip.(mm)

5 24-hr Temp. Anomally

1 12-hr Precip.(mm)

3 24-hr Precip.(mm)

24-hr. Precipitation on Day 5



Forecast
Modelling Programme
of the
Saint John River
Basin

System Organization
Chart

Fig. 12.

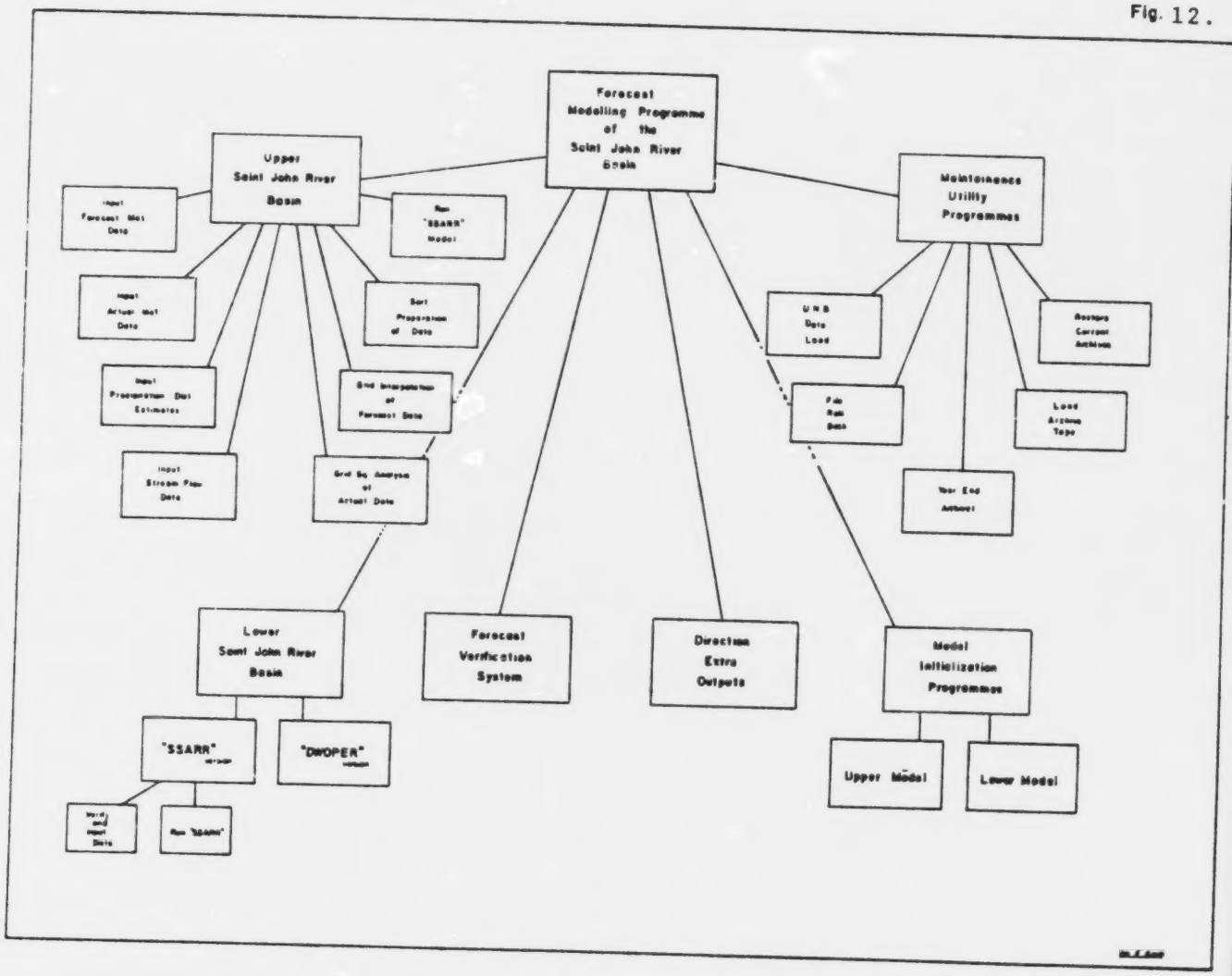
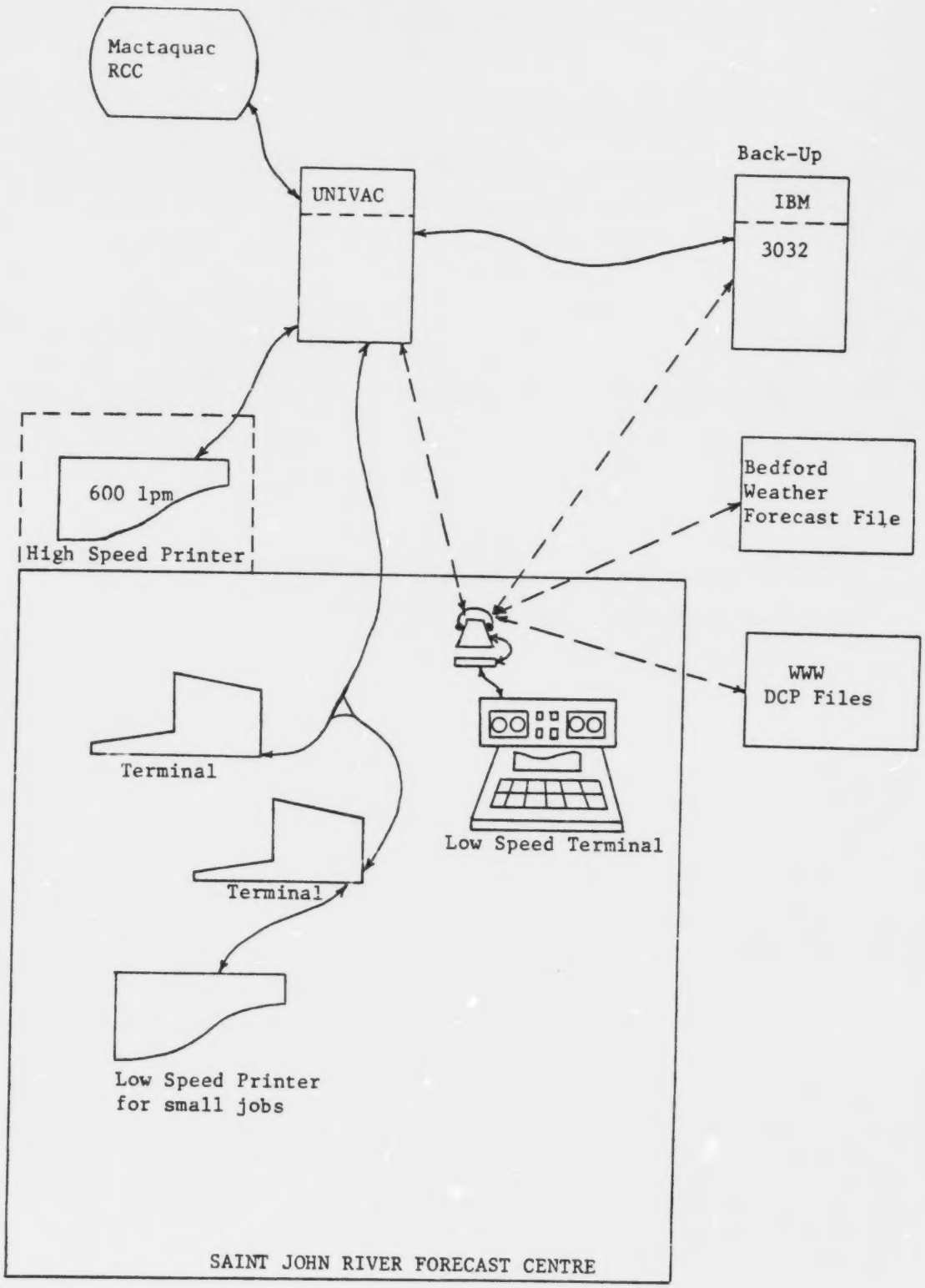
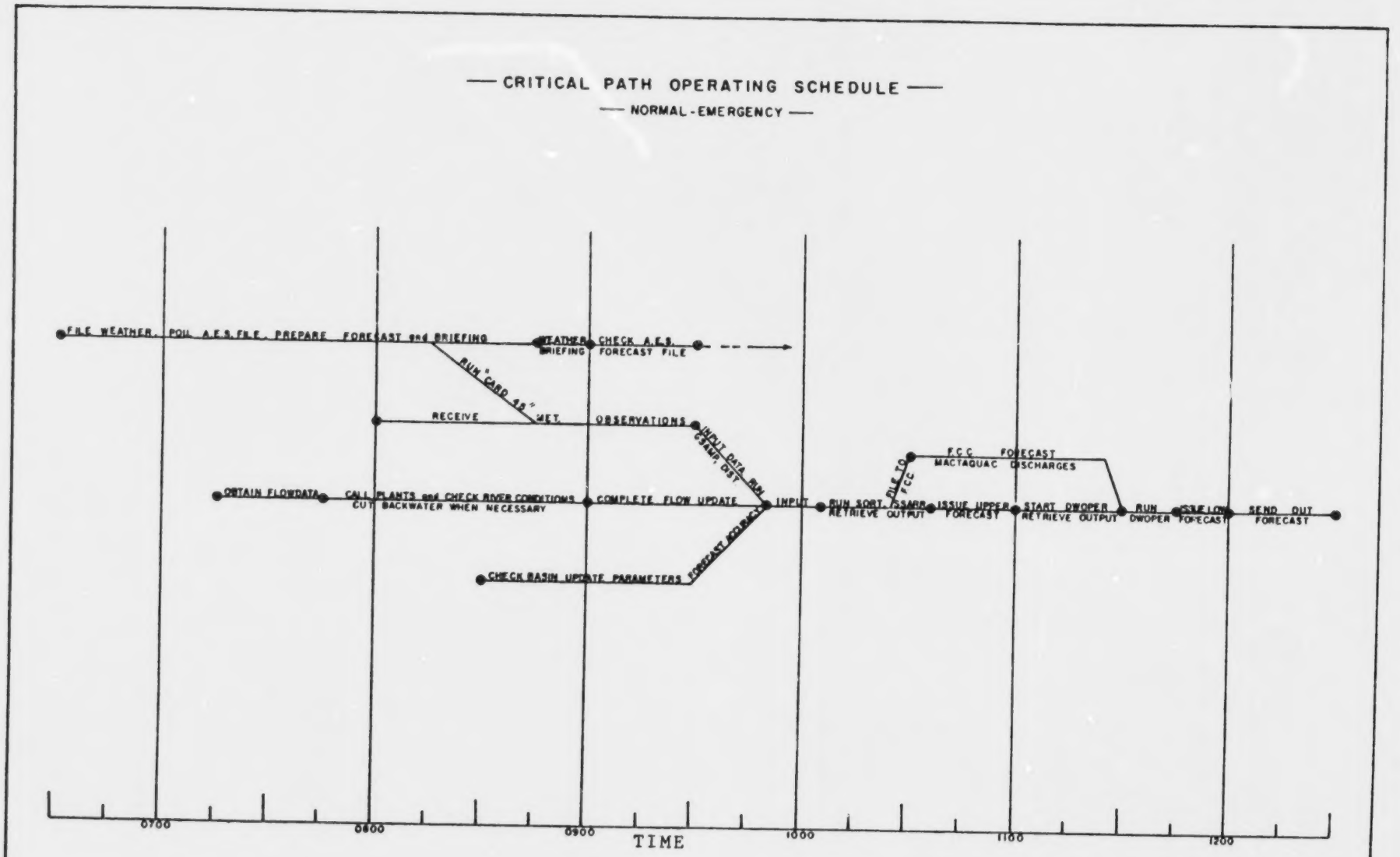


FIG.13. Computing facilities at RFC.





NOTE: CARD45 is the grid interpolation weather forecast program.

Figure 14.

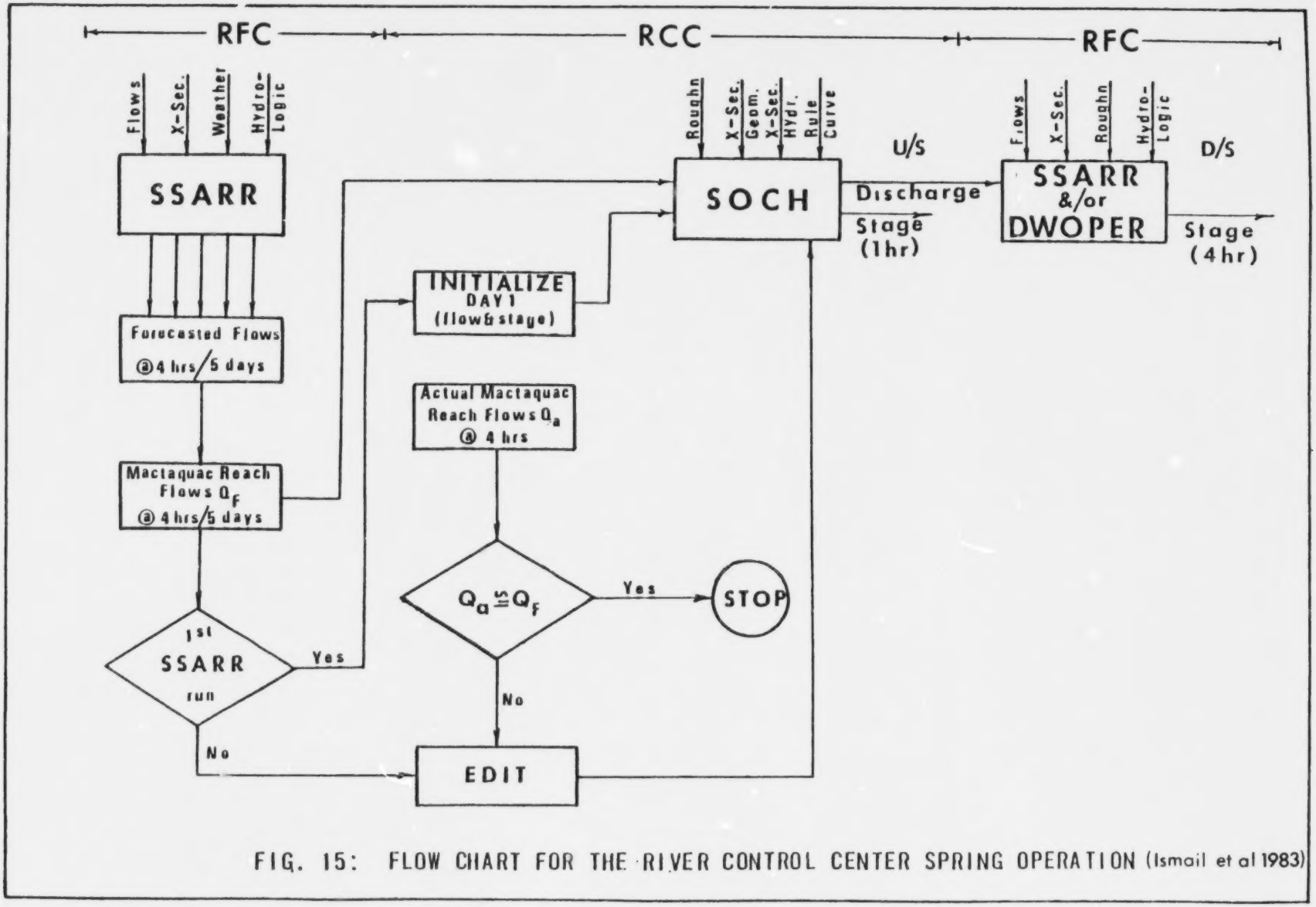


FIG. 15: FLOW CHART FOR THE RIVER CONTROL CENTER SPRING OPERATION (Ismail et al 1983)

SUMMARY

Hydro-Québec Experience in Streamflow Forecasting

by

Jean-Louis Bisson et François Roberge

Hydro-Québec

In this paper, natural inflows forecast model used by Hydro-Québec is described and a few results of this method are shown. This model, which was developed for all year long use, gives a statistical distribution of the forecast inflows. This model is currently used for forecasting inflows of 80 sub-bassins.

The forecast system for each sub-basin can be subdivided into 5 stages:

- the state of the watershed (water in transit and in storage) is calculated from the latest observed meteorological data;
- the state of the watershed is adjusted accordingly to the latest observed hydrometric data;
- with the use of the watershed climatology, the forecasted meteorological data are extended into different possible series of meteorological data;
- with the use of the deterministic conceptual model, the series of inflows corresponding to the meteorological series are calculated;
- the forecasted inflows for different exceedence probabilities are extracted from the simulated inflows series.

A technique has been developed to give a scenario-type freshet hydrograph: the probable peak flow is incorporated into the hydrograph while the forecasted volume is preserved.

The current work on the system concerns the application of Sorooshian and Dracup method to the calibration of the conceptual model to keep a better account of the heteroscedasticity (changing variance) of the inflow data. We are also working on the way to better reflect the uncertainty of the observed data in the short term forecast of inflows.

PREVISION DES APPORTS NATURELS:
EXPERIENCE D'HYDRO-QUEBEC

par

MM. Jean-Louis Bisson et François Roberge
Hydro-Québec

1. Introduction

L'Hydro-Québec est une compagnie d'utilité publique fournissant aux habitants du Québec l'énergie électrique qui leur est nécessaire. Pratiquement toute l'énergie produite par Hydro-Québec est d'origine hydraulique: en effet moins de 1% de l'énergie produite provient de centrales thermiques (ou nucléaires), installées la plupart aux sites isolés de la province.

Pour une compagnie hydro-électrique, la gestion des ressources hydriques doit se faire de manière à assurer l'équilibre consommation-production de l'énergie électrique dans les meilleures conditions de fiabilité et d'économie, tout en respectant l'environnement. Parmi les données nécessaires à une gestion optimale des ressources hydriques, la prévision des apports naturels est de la plus haute importance.

Jusqu'en 1976, la prévision des apports naturels était accomplie par une combinaison de différentes techniques comme l'analyse intuitive des prévisions météorologiques et des conditions hydrologiques et l'application sur le volume total de crue de modèles de régression linéaire par corrélation multiple de différentes données météorologiques. En 1976, nous avons mis en application un modèle développé pour tenir compte principalement de la puissance de calcul des ordinateurs modernes et des données météorologiques et hydrométriques reçues quotidiennement. Ce modèle visait, par son utilisation continue à longueur d'année, la prévision de la distribution statistique des apports naturels et la communication rapide des prévisions à leurs utilisateurs.

2. Description du modèle

2.1 Modèle déterministe Météo-apports

A Hydro-Québec, on a développé un modèle déterministe simple d'explication par les données météorologiques des apports naturels provenant d'un bassin versant de rivière. Ce modèle météo-apports est paramétrique, à bilan hydrique, à deux niveaux de réserve d'eau et à trois types de ruissellement. Les données météorologiques utilisées sont les données quotidiennes de précipitation (pluie et neige) et de température (maximum et minimum). On a choisi ces données météorologiques parce qu'elles étaient les seules données disponibles pour la plupart des bassins versants des rivières exploitées par Hydro-Québec.

2.2 Organisation informatique

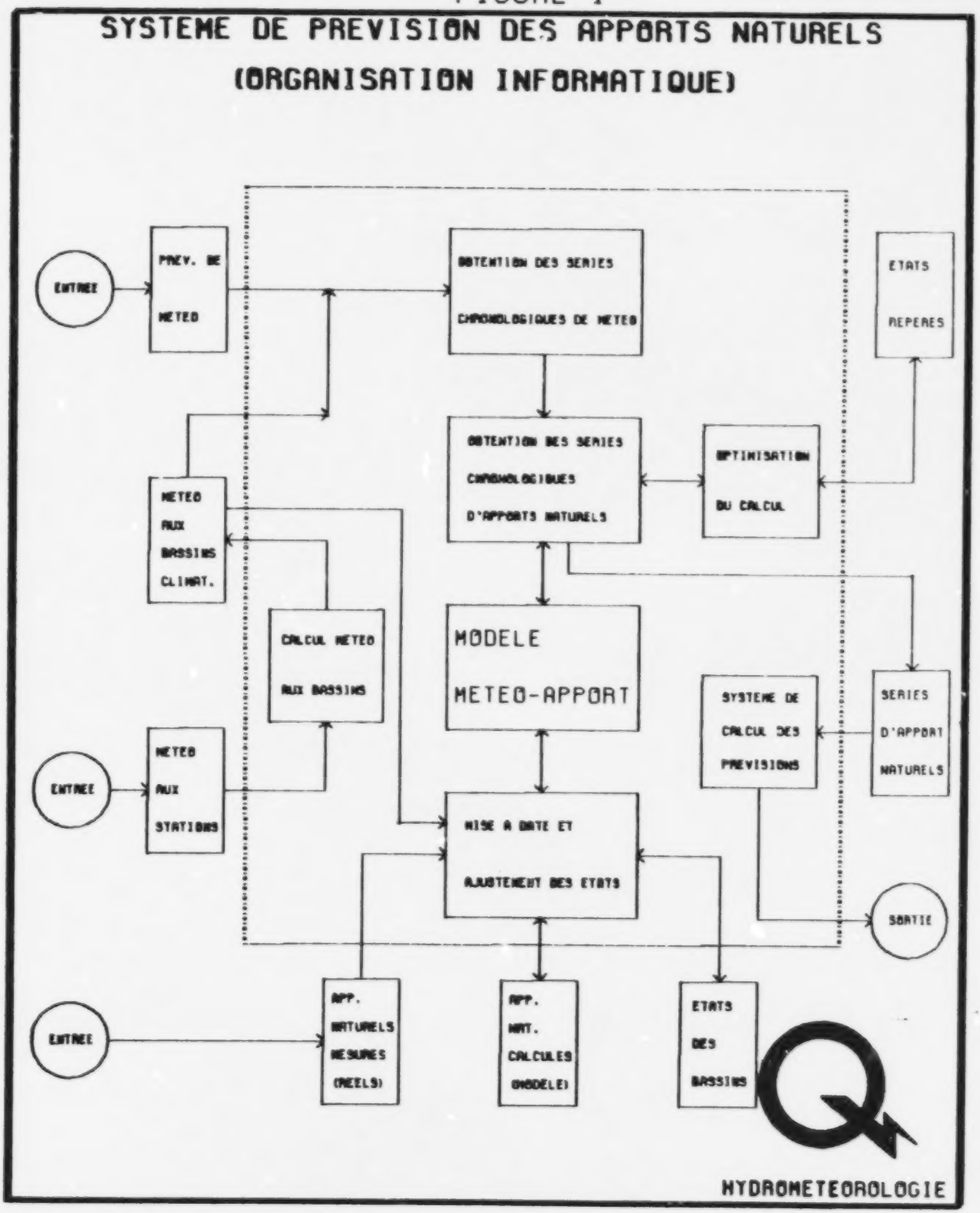
On trouve à la figure 1 le schéma de l'organisation informatique du système de prévision des apports naturels dont le coeur est le modèle déterministe météo-apports. Ce système fonctionne sur l'ordinateur IBM 4341-1 de Gestion du réseau d'Hydro-Québec.

A l'intérieur du cadre pointillé de la figure 1, sont indiqués les modules comprenant les programmes et sous-routines de traitement des données d'entrée et de sortie qui, elles, se trouvent sur la figure à l'extérieur du cadre pointillé. On reçoit quotidiennement des données météorologiques (pluie, neige, températures) de plus de 60 stations météorologiques et les apports de quelques 80 bassins versants sont traités quotidiennement (calcul des apports à partir des lectures du niveau et du débit des points de contrôle, émission des prévisions météorologiques et exécution des programmes).

2.3 Système de prévision

La figure 2 montre la schématisation du système de prévision des apports naturels. En fait, on y distingue cinq étapes principales, soit la mise à date de l'état du bassin à l'aide des dernières données de météo connues, l'ajustement de cet état à l'aide des dernières données hydrologiques disponibles, la formation de séries chronologiques météorologiques suivie du calcul de séries chronologiques d'apports naturels à l'aide du modèle mathématique météo-apports et finalement, le traitement des séries ainsi construites pour en extraire les prévisions demandées.

FIGURE 1


SYSTEME DE PREVISION DES APPORTS NATURELS
(ORGANISATION INFORMATIQUE)
ENTREE
PREV. DE METEO
OBTENTION DES SERIES CHRONOLOGIQUES DE METEO
ETATS REPERES
OBTENTION DES SERIES CHRONOLOGIQUES D'APPORTS NATURELS
OPTIMISATION DU CALCUL
METEO AUX BASSINS CLIMAT.
CALCUL METEO AUX BASSINS
MODELE METEO-APPORT
SYSTEME DE CALCUL DES PREVISIONS
SERIES D'APPORT NATURELS
ENTREE
METEO AUX STATIONS
MISE A DATE ET AJUSTEMENT DES ETATS
SORTIE
ENTREE
APP. NATURELS MESURES (REELS)
APP. NAT. CALCULES (MODELE)
ETATS DES BASSINS
HYDROMETEOROLOGIE

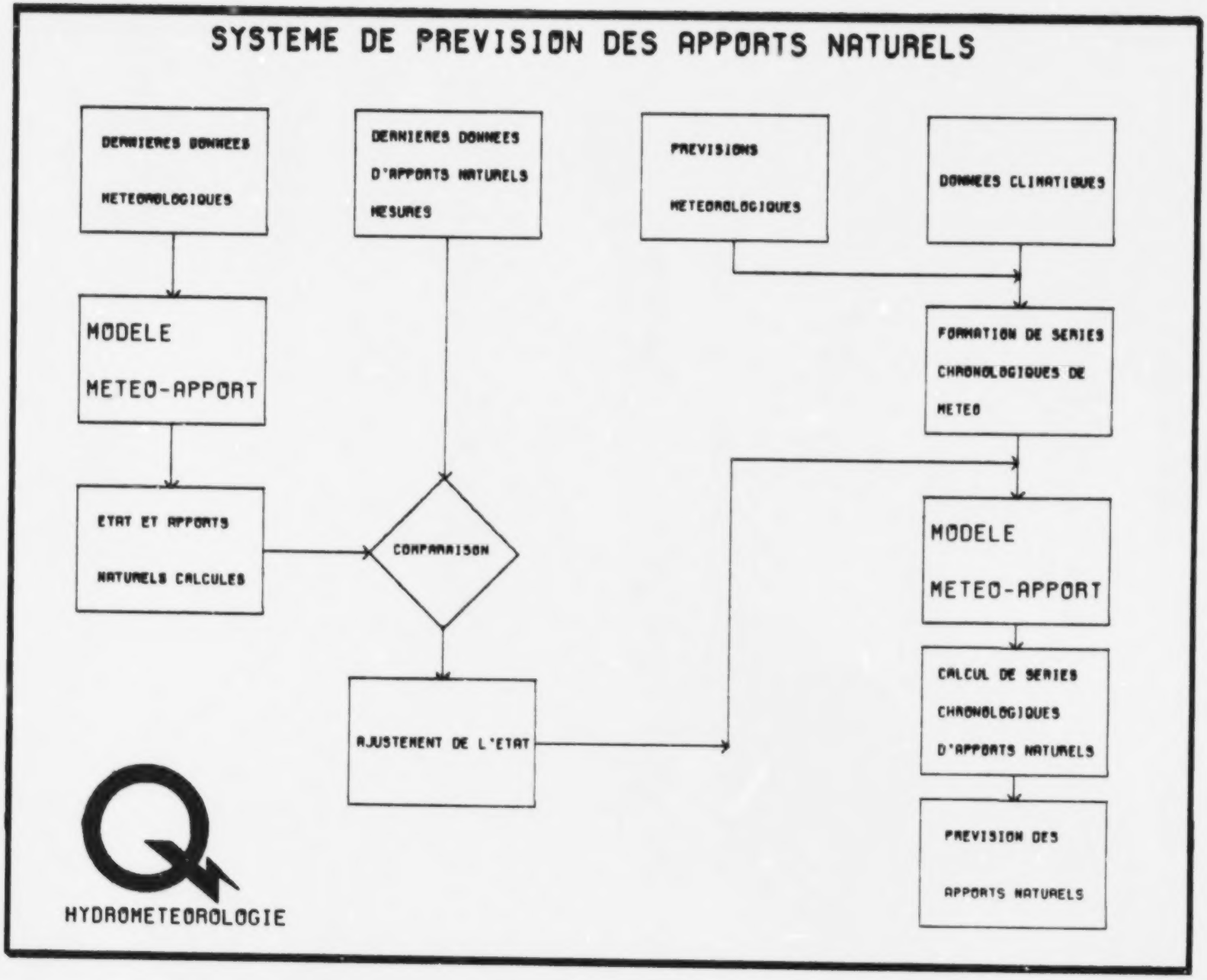

SYSTEME DE PREVISION DES APPORTS NATURELS
DERNIERES DONNEES METEOROLOGIQUES
DERNIERES DONNEES D'APPORTS NATURELS MESURES
PREVISIONS METEOROLOGIQUES
DONNEES CLIMATIQUES
MODELE METEO-APPORT
FORMATION DE SERIES CHRONOLOGIQUES DE METEO
ETAT ET APPORTS NATURELS CALCULES
COMPARAISON
MODELE METEO-APPORT
AJUSTEMENT DE L'ETAT
CALCUL DE SERIES CHRONOLOGIQUES D'APPORTS NATURELS
PREVISION DES APPORTS NATURELS
HYDROMETEOROLOGIE

FIGURE 2

2.3.1 Calcul de l'état du bassin

Les données météorologiques passées comprennent les températures maximale et minimale enregistrées à la station témoin du bassin considéré. A l'aide de ces deux températures, on calcule l'évapotranspiration potentielle correspondant à cette journée. Les précipitations (pluie et neige) mesurées aux différentes stations sont transmises au programme de calcul des précipitations au bassin qui fournit la précipitation moyenne sur le bassin.

Ces données météorologiques sont utilisées comme entrées au modèle déterministe météo-apports qui calcule les apports naturels journaliers correspondants et, par le fait même, l'état hydrologique du bassin (l'ensemble des paramètres calibrés et des variables résumant l'information sur l'eau en stockage et en transit dans le bassin).

2.3.2 Ajustement de l'état du bassin

Dans cette étape, les apports naturels mesurés durant les quelques derniers jours disponibles sont comparés aux apports calculés à l'étape précédente: l'état du bassin est modifié pour rapprocher le plus possible les valeurs calculées et réelles des derniers apports naturels. Les corrections sont appliquées sur une ou quelques variables de l'état dépendant de la saison et des conditions prévalant au sol (neige, fonte, etc...).

2.3.3 Formation des séries chronologiques de météo

Les étapes de la formation de ces séries sont les suivantes:

a) Prévisions météorologiques: Le météorologiste prévoit pour 4 ou 5 jours les valeurs les plus probables des quatres variables des séries chronologiques (pluie, neige, températures maximale et minimale) de même que les deux "extrêmes" possibles que prendront ces variables (ces extrêmes correspondent intuitivement à une dispersion standard). La fin de la période prévue correspond au moment où les prévisions ne sont pas meilleures que la climatologie.

b) Séries climatiques: On dispose de 33 années de données météorologiques quotidiennes sur le bassin considéré (de 1950 à 1982 inclusivement). Ces séries climatiques étant indépendantes entre elles (pour une date donnée), on peut les considérer comme autant de simulations de cas possibles (événements météorologiques) sur le bassin considéré.

c) Séries chronologiques: La formation des séries chronologiques de météo consiste à abouter successivement aux prévisions météorologiques les séries climatiques correspondant aux dates données.

2.3.4 Calcul des séries chronologiques d'apports naturels

Chaque série chronologique de météo génère, selon les équations du modèle déterministe Météo-apports, une série correspondante d'apports naturels. Comme chaque série météorologique est également probable, les séries hydrologiques sont aussi également probables. En effet, ayant vérifié que le modèle déterministe n'introduit pas de biais systématique, l'indépendance des séries de météo est conservée dans les séries hydrologiques.

Simulation d'une série d'apports naturels à un bassin:

0	5	799 jours
Données passées Etat mis à date au jour 0	Simulation à l'aide des prévisions météorologiques (4 à 5 jours)	Simulation à l'aide d'une série climatique.

Ces séries simulées tiennent compte de la météo passée, des apports naturels passés, de l'état actuel du bassin et des prévisions météorologiques. Toute l'information utilisable dans une prévision d'apports naturels est incluse dans le processus de la prévision. Il faut noter aussi que la technique utilisée demeure la même quelle que soit l'échéance de la prévision; ce qui conserve la continuité et la concomitance des simulations.

À la fin de cette étape, nous disposons de 33 séries d'apports naturels de 799 jours par bassin.

2.3.5 Prévision des apports naturels

Le traitement statistique des séries d'apports naturels simulés, auxquels on inclut l'erreur due aux déficiences du système, permet d'obtenir la prévision probabilistique des apports naturels. Parmi de nombreuses possibilités, on peut extraire à un niveau de probabilité spécifié la prévision d'apports journaliers, de volumes d'apports, de dates de pointe, de dates de début ou de fin de crue, etc...

Pour les besoins de planification de l'utilisation des ressources hydriques d'Hydro-Québec, la prévision des volumes d'apports est demandée mais pour les besoins de sécurité des ouvrages hydro-électriques et pour le respect des contraintes environnementales, la prévision de la pointe est aussi nécessaire.

La prévision des apports naturels est fournie sous forme d'hydrogramme selon le pas de temps exigé (jour, semaine, mois) et couvrant la période demandée. La formule appliquée est la suivante:

$$Q_t^p = Q_t^m + X_t^p$$

et

$$X_t^p = (V^p - V^m)\, U_t$$

où Q_t^p = apport naturel au temps t et de probabilité au dépassement p;

Q_t^m = apport naturel médian au temps t selon les simulations;

X_t^p = correction à appliquer au temps t selon la probabilité au dépassement p;

V^p = volume de probabilité au dépassement p selon les simulation ,

V^m = volume médian selon les simulations;

U_t = pourcentage de correction tenant compte de la variabilité naturelle des apports au temps t.

Cette formule respecte le volume et l'allure générale des apports naturels. Cependant, la technique utilisée a tendance à "écraser" l'hydrogramme quelque peu; ce qui entraîne certains inconvénients en période de pointe (sous-estimation) et d'étiage (sur-estimation).

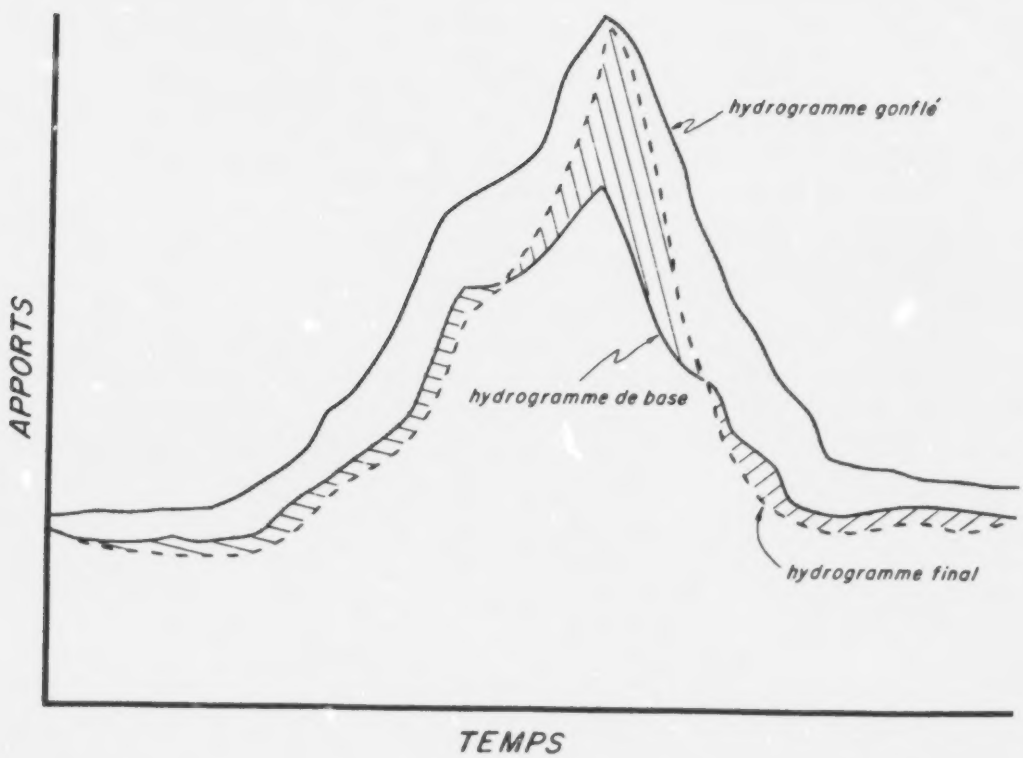
Comme les problèmes reliés à la pointe sont souvent majeurs, nous avons développé une technique (de type graphique) basée sur les probabilités conditionnelles qui permet un réarrangement de l'hydrogramme de sortie de façon à conserver son allure générale tout en fournissant des valeurs de pointes plus réalistes.

La technique utilisée peut se résumer par les points suivants:

- Recherche, parmi les séries simulées, de celles dont le volume se rapproche du volume demandé;
- Identification de la valeur de la pointe la plus probable pour le volume demandé à l'aide de lois statistiques;
- Indroduction de cette valeur dans l'hydrogramme à la journée correspondante à la pointe de cet hydrogramme;
- Etape montée: gonflement de l'ensemble de l'hydrogramme de façon à atteindre la pointe désirée; ce gonflement suit les mêmes règles que décrites précédemment, i.e. respect de la variance quotidienne des apports;

. Etape descente: ramener le volume de l'hydrogramme gonflé au volume demandé par une technique de poids qui respecte les points suivants:
  . le début de l'hydrogramme final doit être le plus près possible des valeurs de l'hydrogramme de base;
  . le surplus de volume autour de la pointe doit être compensé le plus possible sur les valeurs autour de la moyenne de l'hydrogramme;
  . les valeurs finales ne doivent pas excéder les valeurs minimales ou maximales enregistrées par toutes les séries simulées.

Schéma type:



3. Evaluation des résultats

Afin de donner un aperçu général de l'efficacité et de la précision des prévisions d'apports naturels, nous présentons, au tableau 1, quelques indices de précision calculés sur certains bassins représentatifs des différentes régions qui nous intéressent.

Les bassins choisis sont les suivants:

- Dozois: région Abitibi (Outaouais Supérieur);
- Baskatong: Outaouais moyen, (Nord de la rivière Gatineau);
- Coulonge: Outaouais moyen, Ouest;
- South Nation: Outaouais Inférieur;
- Rapide Blanc: St-Maurice;
- Bersimis 1: Côte-Nord, Est du Québec; rivière Bersimis;
- Manic 5: Côte-Nord, Est du Québec; rivière Manicouagan.

Les résultats sont compilés de 1979 à 1983 (lorsque les données sont disponibles) sur la période de crue (début mars à fin juillet environ) et portent sur les prévisions à court terme (de 1 à 18 jours de prévision).

Les indices de précision utilisés sont les suivants:

- coefficient de Nash

$$CNA = \frac{\sum [(Qobs(i) - \overline{Qobs})^2] - \sum [(Qobs(i) - Qcal(i)^2]}{\sum [(Qobs(i) - \overline{Qobs})^2]}$$

- coefficient de pointe

$$CP = \frac{\left\{\sum [(Qobs(i) - Qcal(i))^2 \times (Qobs(i)^2]\right\}^{1/4}}{[\sum (Qobs(i))^2]^{1/2}}$$

- coefficient de volume

$$CV = \frac{\sum (Qobs(i) - Qcal(i)) \times \Delta T}{Q\,MAX \times T}$$

- coefficient final

$$CF = (1 - CNA) + (2 \times CP) + CV.$$

Signification des coefficients:

- *Le coefficient de NASH:CNA mesure la qualité générale de la prévision sur toute la période analysée, avec un poids égal donné aux fortes et aux faibles valeurs. (Prévision parfaite, CNA = 1.0)*
- *Le coefficient de POINTE:CP mesure la qualité de la reproduction de l'hydrogramme de crue. S'il est mauvais cela indique que la forme de l'hydrogramme n'est pas bien reproduite surtout pour les forts débits. (Prévision parfaite, CP = 0.0)*
- *Le coefficient de VOLUME:CV mesure la qualité de la reproduction du bilan hydrique pour toute la période analysée, (Prévision parfaite, CV = 0.0)*
- *Afin de tenir compte de ces trois critères dans l'appréciation globale d'une prévision on utilise le coefficient FINAL: CF qui donne une indication globale de la qualité de la prévision. (Prévision parfaite, CF = 0.0) (Prévision acceptable, CF ≥ 1.25)*

Comme guide d'appréciation, nous retenons les valeurs suivantes:

Pour le coefficient de NASH:CNA
CNA ≥ 0.80: prévision de grande qualité fiabilité excellente;
0.60 ≤ CNA < 0.80: prévision acceptable bonne fiabilité;
CNA < 0.60: prévision passable imprécision trop élevée.

Pour le coefficient final: CF
Le nombre de jours prévus à l'avance dont le CF demeure > 1.25 est:
> 18 : excellente prévision tant du point de vue volume que valeurs journalières (pointes et concomitance);
>10 et ≤ 18 : bonne fiabilité des prévisions imprécision acceptable;
>5 et ≤ 10 : fiabilité moindre imprécision assez élevée;
≤5 : grande imprécision prévision déficiente.

On doit cependant noter qu'une valeur faible des indices est généralement le signe d'une mauvaise qualité des données de base (météo et surtout hydraulique) et n'indique pas nécessairement un problème structurel du système de prévision (calibration du modèle ou autre). Enfin, la difficulté de prévoir les grandes variations de la météorologie (plus que 4 jours à l'avance) explique, en grande partie, l'imprécision des prévisions d'apports.

TABLEAU 1: CALCUL DES INDICES

Bassin	Année	Coeff. de Nash (CNA) sur le Xième jour prévu à l'avance				Journée où le CF ≥ 1.25
		1	3	5	10	
Dozois	79	.81	.72	.62	.48	16
	80	.80	.80	.77	.65	16
	81	.58	.52	.16	.0	5
	82	.70	.70	.70	.73	18
	83	.80	.76	.72	.67	18
Baskatong	79	.88	.74	.62	.44	10
	80	.86	.84	.86	.69	13
	81	.93	.87	.80	.43	11
	82	.93	.90	.85	.75	18
	83	.95	.90	.85	.60	18
Coulonge	79	.90	.80	.73	.58	18
	80	.97	.92	.92	.61	11
	81	.91	.92	.84	.57	12
	82	.98	.97	.94	.89	18
	83	.90	.80	.64	.49	18
South Nation	79	.66	.62	.65	.20	8
	80	.89	.61	.31	.0	4
	81	.91	.88	.85	.38	9
	82	.88	.81	.69	.12	6
	83	.64	.69	.49	.20	6
Rapide Blanc	82	.93	.90	.88	.90	18
	83	.92	.85	.72	.53	11
Bersimis 1	82	.91	.85	.75	.53	18
	83	.70	.42	.34	.0	7
Manic 5	82	.88	.86	.74	.77	18
	83	.77	.69	.62	.46	12

4. Projets à l'étude

Ce système de prévision est opérationnel depuis près de 8 ans avec efficacité et fiabilité. Cependant, dans le but d'améliorer et d'optimiser son rendement, plusieurs modifications sont apparues au fil des ans. Ainsi, le modèle déterministe a subi plusieurs transformations (raffinements) qui permettent une meilleure réponse au printemps en période de pointe. De plus, une attention particulière fut donnée sur l'évaluation de la pointe conditionnelle ou volume prévu.

Plus récemment, on a examiné de plus près différentes techniques d'ajustement pour la calibration des paramètres du modèle. Ainsi, Sorooshian, S. et Dracup, J.A. (1980) ont développé une méthode d'estimation basée sur l'hypothèse d'une variance mobile des erreurs sur la mesure des apports qui améliore sensiblement le rendement du modèle. Nous sommes à mettre au point cette nouvelle approche et les résultats préliminaires sont très positifs.

Enfin, concernant la qualité des prévisions à court terme, nous travaillons présentement sur l'introduction d'éléments aléatoires qui, tout en respectant l'allure générale des prévisions, refléteraient mieux l'incertitude des données mesurées (erreurs sur les données météo et hydrauliques). Ainsi, nos recherches portent sur deux aspects principaux:

1. la variabilité des événements futurs possibles;

2. l'incertitude relative de l'état du bassin au jour 0 (l'état initial comprenant certaines variables dont l'estimation s'accompagne d'un delta d'incertitude).

BIBLIOGRAPHIE

Sorooshian S. and Dracup J.A.:
Stochastic Parameter Estimation Procedures for Hydrologic Rainfall-Runoff Models: Corrolated and Heteroscedastic Error Cases, Water Resources Research 16(2), 430-441, 1980.

STATUS

OF THE AUTOMATION OF THE

ONTARIO STREAMFLOW FORECAST CENTRE

BY

P. N. GRYNIEWSKI

NOVEMBER 22, 1983

Introduction

Over time, the demands for flood forecasts have changed from a simple indication of severity of flooding to the expectation of an accurate magnitude and timing of a flood passage. In order to meet the demand and provide the expected forecasts, an increase in resources becomes necessary. In Ontario, streamflow forecasting was commenced by Mr. J. P. Bruce after Hurricane Hazel occurred in 1954. Over the years, the staff has grown to four persons: a supervisor, a unit head, a forecaster and a technician.

The data accessible has grown from 130 mostly manually-observed streamflow stations in 1956 to 500 recording gauges today. Of these, 150 have telemetering capabilities. Snow courses observed by the Ministry and Conservation Authorities first started in 1956 and today number some 175. Precipitation measurement has gone from twice-daily rain gauges to telemetered sensors and radar images.

With the desire to free some of the time taken in data collection and analysis, as well as running of models, and allow more time for interpretation, a project was commenced to computerize the Streamflow Forecast Centre and provide products never available before.

Background

A few years ago considerable interest was generated by the announcement that Ontario was about to enter into a computerized, highly automated forecasting system. This had followed on heels of a feasibility study and the preparation of a request for proposal that data collection, transmission, analysis and forecasting be done automatically. A budget was prepared, and the project was tendered.

Contract

After an internal Feasibility Study, a Request for Proposal was prepared which was bid on by five contractors. Goodwood Data Systems was the successful low bidder and commenced a six-month contract to:

(a) Develop software;

(b) Lease a computer to run the system;

(c) Develop specialized hardware such as a radar storage and computation system and a special data logger.

Unfortunately, the contractor went into receivership after three years and the assets were dispersed.

Products Expected

A. Teletype:

The users or clients of the system, including Ministry Regional Offices, Conservation Authorities and other agencies such as Ontario Hydro, Water Survey and the Canal Systems, would be able to obtain decoded weather information from AES teletype line 278.

B. Digital Radar:

Printouts to clients.

C. Data Collection Platform and Data Logger:

Decoded printouts and plots.

D. Manual Sources:

Printouts.

E. Running of Forecast Models. Calibration, Double Mass Analysis.

F. Archiving.

G. Displaying Data.

H. Development of a Specialized Data Logger:

Sensor inputs and keypad for entry of gate, valve and stoplog settings. Sensors include water level, precipitation and temperature. Inflow calculations and plots.

I. Radar:

Storage, retrieval, display of radar images for 24 hours. Accumulation maps of precipitation for various intervals; e.g. six hourly. Calibration of ground stations with radar pixels. Computation of mean basin precipitation for use in a forecast model.

J. Job Streams:

1. Data acquisition 24 hours per day from AES network, DCP, weather radars and manual sources.
2. Selection of modeling periods (e.g. six hours) and watersheds (basin boundaries) and initiation of streamflow forecasting functions (flow, precipitation, temperature and calibration parameters).
3. Intermittent requests for map plotting, data display and program development.

Products Delivered

A. AES Teletype Traffic:

1. Forecasts
   - Weather Forecasts
   - Outlooks
   - Meteorologist's interpretation
   - QPF
   - LFM
   - Severe Weather
   - Thunderstorm
2. Observations
   - Hourlies
   - 6 hourly synoptics
   - 6 hourly precipitation

B. Digital Radar Printouts:

- CAPPI
- Accumulations

C. Data Collection Platform and Data Logger Printouts.

F. Archiving:

- Partially complete, disc to tape.

G. Displaying Data.

I. Radar:

- Woodbridge CAPPI for 24 hours
- Exeter CAPPI for 6 hours

Accumulation 6 hours Woodbridge and Exeter

J. Job Streams:

1. Data Acquisition.

New Feasibility Study

After the contractor went into receivership, the Ministry purchased the computer hardware and software. A feasibility study was done by an outside consultant that has recommended:

A. Upgrading operating software from RDOS to AOS.

B. Augmentation of hardware.

C. Additional applications software.

D. Off-the-shelf data logger.

Observations and Conclusions

Our most important function will be to have the system running in as short a time as possible. Because of the availability of many data loggers now, the one developed here will have the lowest priority. With the experience gained in attempting to run the NWSRFS model, we will be taking a hard look at whether to expend much time in developing this further. The problem we see is that to use it for real-time forecasting requires a great deal of staff time to adjust the parameters on a daily basis to keep the model on track. We may be defeating our purpose of obtaining more time for interpretation by spending too much time adjusting the model, where a simple model may be sufficient.

Future Directions

The SHARP system developed by the McGill Radar group shows considerable promise in being able to project rainfall ahead on a radar image and determine hourly values of mean basin precipitation for a given watershed.

Appendices

Examples of Products

The following pages give examples of the products presently available from the system.

```
C   ab
?
C AB,10
  1 = ABUS3 KWBC 211417
  2 = ABUS2 KWBC 211417
  3 = ABUS1 KWBC 211417
  4 = ABUS3 KWBC 210900
  5 = ABUS2 KWBC 210900
  6 = ABUS1 KWBC 210900
  7 = ABUS3 KWBC 210752
  8 = ABUS2 KWBC 210752
  9 = ABUS3 KWBC 210217
 10 = ABUS2 KWBC 210217

C   1-3

ABUS3 KWBC 211417
NAT WEA SUM  PT 3
THE NATIONAL WEATHER FORECAST FOR FRIDAY...THUNDERSTORMS WILL
REMAIN OVER THE EASTERN QUARTER OF TEXAS.  RAIN AND OCCASIONAL
THUNDERSHOWERS WILL REACH FROM OKLAHOMA TO SOUTHEAST NEBRASKA
...FROM IOWA THROUGH ARKANSAS...FROM SOUTHERN WISCONSIN ACROSS
THE OHIO VALLEY AND THE CENTRAL ATLANTIC COAST...AND FROM SOUTH
CAROLINA ACROSS MARYLAND.  RAINSHOWERS WILL ALSO EXTEND OVER THE
NORTHERN PACIFIC COAST.  HIGH TEMPERATURES WILL REACH THE 40S
ACROSS NEW ENGLAND...WITH THE 50S FROM NEW YORK STATE AND
PENNSYLVANIA TO THE DAKOTAS THROUGH OKLAHOMA.  HIGHS IN THE 80S
WILL REACH FROM FLORIDA ACROSS THE GULF STATES THROUGH EASTERN
TEXAS...WITH THE INLAND SOUTHWEST REACHING THE 80S AND LOW 90S.
HIGH TEMPERATURES OVER THE REMAINDER OF THE NATION WILL REACH
THE 60S AND 70S.
PREDICTED MAP POSITIONS FOR 7 AM CDT SATURDAY...A STATIONARY
FRONT WILL REACH FROM CENTRAL WEST VIRGINIA TO A LOW OVER
SOUTHERN ILLINOIS.  A COLD FRONT WILL CONTINUE FROM THE LOW
ACROSS WESTERN TENNESSEE...NORTHEAST LOUISIANA AND THE TEXAS
COAST TO SOUTHERN TEXAS.  A COLD FRONT WILL REACH FROM NORTHWEST
MINNESOTA ACROSS NORTHEAST MANITOBA.  A COLD FRONT WILL CURVE
OVER CENTRAL ALBERTA...NORTHWEST MONTANA...NORTHEAST OREGON AND
THE NORTHERN COAST OF CALIFORNIA INTO THE PACIFIC OCEAN.  A WARM
FRONT WILL EXTEND FROM NORTHEAST MONTANA TO JOIN THE COLD FRONT
OVER CENTRAL ALBERTA.  HIGHS WILL BE OVER CENTRAL COLORADO AND
WEST CENTRAL NEW ENGLAND.
HUGH CROWTHER
NATIONAL PUBLIC SERVICE UNIT
```

```
FMCN3 CWAD4 211600
YBR  0 16  2 16 YWG  5 15  4 16 YQK  6 12  7 14
YQT  2 13  8 15 YYW  1 12  2 13 WPL  6 10  3 12
WTL  2 11  3 12 WIB  3 15  6 17 WLH  5 11  5 11
YRL  4 11  5 13 YXL  4 12  5 14 YQD  2 13  3 13
YYL  0 11  2 11 YDN  3 16  4 16 WGU  2 13  3 13
YTH -1 10  1 11 YYQ -2  5  0  7 WEI -3  3 -1  6
YSM  1  9 -2  9 YZF -1  4  0  5 YBE  1  9  1  9
```

```
FMCN1 CWWG 261415
YWG  3/20
YQT  0/13
YQR  2/16
```

```
FMCN2 CYYZ 260900
TEMPERATURE FORECAST BULLETIN ISSUED BY ENVIRONMENT
CANADA AT 5AM EDT  OCTOBER  26  1983.
                  HIGH   LOW  HIGH
                 TODAY  TNGT  TMRW
WINDSOR             12     3    14
SARNIA              10     2    12
ST THOMAS           11     2    12
LONDON              11     2    12
KITCHENER           10     1    11
MOUNT FOREST         9  ZERO    10
WINGHAM             10     1    11
OWEN SOUND          10     2    10
MUSKOKA              8  ZERO    10
HAMILTON            10     2    11
ST CATHARINES       11     2    11
TORONTO             11     3    12
TRENTON             10     1    10
KINGSTON            10     1    10
PETERBOROUGH        10  ZERO    10
PETAWAWA             9    M1     9
NORTH BAY            8    M1     9
SUDBURY              8  ZERO    10
EARLTON              7    M2     8
TIMMINS              6    M3     7
KAPUSKASING          6    M4     7
SAULT STE MARIE      9  ZERO    11
WAWA                 7    M2     9
WHITE RIVER          6    M3     8
GERALDTON            7    M1    11
MOOSONEE             5    M4     6
END
```

FXCN05 CWAO1 211740

PROB OF PCPN IN 4 RANGES: OVER 0.2MM, 0.2-2MM, 2-10MM, OVER 10MM

	TODAY								SATURDAY								SUNDAY							
	12-24Z				00-12Z				12-24Z				00-12Z				12-24Z							
YQG	8	5	3	0/	8	5	2	1/	54	17	36	1/	98	41	45	12/	72	19	36	17				
YXU	2	2	0	0/	2	1	1	0/	3	3	0	0/	65	17	5	13/	99	31	42	27				
YYZ	1	1	0	0/	2	1	1	0/	1	1	0	0/	65	15	32	18/	88	33	38	17				
YTR	1	1	0	0/	0	0	0	0/	1	1	0	0/	29	8	14	7/	51	24	21	6				
YVV	0	0	0	0/	0	0	0	0/	9	1	8	0/	72	19	39	14/	55	2	36	17				
YOW	1	1	0	0/	1	1	0	0/	1	1	0	0/	6	6	0	0/	57	28	24	5				
YYB	0	0	0	0/	0	0	0	0/	5	4	1	0/	75	17	34	24/	80	44	26	10				
YAM	0	0	0	0/	2	1	1	0/	38	17	20	1/	99	23	39	38/	73	18	27	28				
YXR	1	1	0	0/	0	0	0	0/	1	1	0	0/	72	21	34	17/	70	24	30	16				
YYU	2	2	0	0/	2	2	0	0/	8	8	0	0/	55	6	35	14/	32	12	11	9				
YMO	3	3	0	0/	13	12	1	0/	3	2	1	0/	12	12	0	0/	10	10	0	0				
YYW	2	2	0	0/	5	4	1	0/	7	6	1	0/	34	16	12	6/	17	3	9	5				
YTL	25	22	3	0/	24	22	2	0/	9	8	1	0/	1	1	0	0/	9	7	0	2				
YOK	3	2	1	0/	3	3	0	0/	1	1	0	0/	11	11	0	0/	12	7	5	0				
YQT	4	3	1	0/	8	5	3	0/	19	9	9	1/	52	21	23	8/	20	8	4	8				

FMCN3 CWA05 260720

MAX, MIN, AND PROB OF PCPN FOR FRI TO SUN

WZC	01/ 13/ 85	-02/ 05/ 50	-06/ 01/ 35
YYU	04/ 15/ 80	00/ 06/ 70	-06/ 02/ 40
WGQ	06/ 12/999	-01/ 05/999	-05/ 03/999
YXZ	05/ 13/ 70	-04/ 06/ 60	-10/ 04/ 40
SSM	08/ 17/999	00/ 07/ 58	-03/ 06/999
YXR	02/ 15/ 60	00/ 08/ 70	-04/ 04/ 40
YVO	-01/ 14/ 68	-01/ 07/ 79	-05/ 00/ 53
YSB	05/ 14/999	01/ 08/999	-03/ 05/999
YTS	02/ 14/999	00/ 07/999	-05/ 03/999
YYB	03/ 14/ 55	02/ 07/ 45	-04/ 03/ 25
YGA	01/ 14/999	02/ 09/999	-04/ 05/999
YZE	07/ 15/999	03/ 08/999	00/ 07/999
YVV	05/ 18/999	04/ 10/999	-01/ 06/999
YQG	05/ 21/ 25	06/ 12/ 30	-02/ 09/ 05
YXU	06/ 16/ 20	02/ 12/ 55	-04/ 09/ 20
YSN	01/ 16/999	09/ 12/999	-02/ 07/999
YHM	02/ 15/999	06/ 14/999	-03/ 09/999
YYZ	02/ 15/ 20	03/ 14/ 35	-04/ 08/ 10
YPQ	-01/ 14/999	06/ 12/999	-04/ 07/999
YTR	01/ 13/ 15	03/ 12/ 25	-03/ 07/ 05
YXI	-01/ 16/ 25	01/ 11/ 30	-05/ 05/ 15
WMW	-03/ 12/999	01/ 10/999	-04/ 03/999
YOW	00/ 12/ 20	02/ 12/ 45	-03/ 05/ 15
YUL	02/ 11/ 20	05/ 13/ 45	-01/ 06/ 10
WOH	-03/ 08/999	02/ 09/999	-02/ 02/999
YRJ	00/ 11/999	02/ 12/999	-04/ 04/999
YSC	-03/ 09/999	03/ 12/999	-04/ 03/999
YQB	-01/ 09/ 35	01/ 11/ 60	-02/ 05/ 05
YBG	00/ 10/ 60	01/ 10/ 85	-02/ 05/ 40
YRQ	-04/ 11/999	03/ 11/999	01/ 06/999
YNM	00/ 13/999	04/ 05/999	-04/ 00/999
YMT	-04/ 10/999	00/ 05/999	-05/ 00/999
YYY	01/ 07/ 45	04/ 12/ 65	01/ 07/ 10
YBC	02/ 08/999	01/ 09/999	-01/ 06/999
WNH	01/ 07/999	04/ 11/999	01/ 04/999
YZV	00/ 07/ 30	00/ 07/ 80	-02/ 06/ 15
YFQ	02/ 08/999	02/ 14/999	01/ 07/999
WYI	01/ 07/999	01/ 07/999	01/ 06/999
YWK	-02/ 03/999	-03/ 06/999	-04/ 00/999
YGA	-02/ 04/999	-01/ 05/999	-03/ 01/999
YGR	04/ 08/999	05/ 10/999	04/ 08/999

FPCN10 CYYZ 210926
SYNOPSIS FOR ONTARIO ISSUED BY ENVIRONMENT CANADA AT 6.30 AM EDT
FRIDAY OCTOBER 21 1983.
SOUTHERN ONTARIO.
A LARGE AREA OF HIGH PRESSURE OVER QUEBEC CONTINUES TO GIVE WINDY
AND COOL WEATHER TO SOUTHERN ONTARIO FOR THE NEXT COUPLE OF DAYS.
BRISK EASTERLY WINDS 40 TO 50 KMH WILL PREVENT THE MERCURY FROM
RISING MUCH ABOVE THE 10 DEGREE MARK. A DISTURBANCE STILL BREWING
OVER THE AMERICAN SOUTHWEST WILL SLOWLY MOVE NORTHEASTWARD SATURDAY.
CLOUDS ASSOCIATED WITH THIS SYSTEM ARE BLANKETING THE EXTREME
SOUTHWEST OF THE PROVINCE TODAY AND WILL GRADUALLY MOVE EASTWARD
TO COVER MOST REGIONS BY SATURDAY NIGHT.
RAIN IN ADVANCE OF THIS SYSTEM WILL BEGIN IN THE WINDSOR AREA
SATURDAY AND WILL BECOME WIDESPREAD THROUGHOUT THE LOWER GREAT
LAKES SUNDAY. IN THE WAKE OF THIS DISTURBANCE WARMER WEATHER
WILL PREVAIL.
NORTHERN ONTARIO.
GENERALLY CLEAR SKIES ALONG WITH SUBFREEZING TEMPERATURES OCCURRED
OVER THE ONTARIO NORTHLAND LAST NIGHT. THE HIGH PRESSURE AREA
RESPONSIBLE FOR THIS WEATHER WILL CONTINUE TO DOMINATE THE SCENARIO
THROUGH SATURDAY. HOWEVER A DISTURBANCE APPROACHING FROM THE
PRAIRIES WILL SPREAD CONSIDERABLE CLOUDINESS TO LOCALITIES NORTH
OF LAKE SUPERIOR LATER TODAY FOLLOWED BY SOME RAIN. THIS WILL
OCCUR MOSTLY IN THE WINISK REGION. ELSEWHERE IN NORTHERN ONTARIO
VERY LITTLE PRECIPITATION OF SIGNIFICANT IS ANTICIPATED THROUGH
THE WEEKEND. IN THE WAKE OF THIS DISTURBANCE MOSTLY SUNNY TO
PARTLY CLOUDY SKIES ALONG WITH MORE PALATABLE TEMPERATURES WILL
PREVAIL.
END

FPCN11 CYYZ 211419
PART 1 OF 2
FORECASTS FOR ONTARIO ISSUED BY ENVIRONMENT CANADA AT 11.00 AM EDT
FRIDAY OCTOBER 21 1983 FOR TODAY AND SATURDAY.
THE NEXT SCHEDULED FORECASTS WILL BE ISSUED AT 3.30 PM EDT TODAY.
METRO TORONTO
SUNNY WITH CLOUDY PERIODS TODAY. BRISK EASTERLY WINDS. LOW NEAR
PLUS 3. SATURDAY SUNNY WITH INCREASING CLOUDINESS. CONTINUING
WINDY. HIGH NEAR 11.
PROBABILITY OF PRECIPITATION ZERO PERCENT TODAY. ZERO PERCENT
TONIGHT. 10 PERCENT SATURDAY.
LAKE ST CLAIR REGION
WINDSOR CITY.
CLOUDY WITH SUNNY PERIODS TODAY. EASTERLY WINDS GUSTING TO 50
KMH. CHANCE OF A SHOWER TONIGHT. LOWS 5 TO 0. CONTINUING WINDY
SATURDAY WITH PERIODS OF RAIN DEVELOPING. HIGHS 11 TO 13.
PROBABILITY OF PRECIPITATION 10 PERCENT TODAY. 30 PERCENT TONIGHT.
80 PERCENT SATURDAY.
SOUTHERN LAKE HURON
LAKE ERIE REGIONS
LONDON
KITCHENER CITIES.
SUNNY WITH CLOUDY PERIODS TODAY. EASTERLY WINDS GUSTING TO 45 KMH.
PARTLY CLOUDY TONIGHT WITH LOWS NEAR 3. SATURDAY INCREASING
CLOUDINESS WITH?A CHANCE OF A SHOWER LATE IN THE DAY.
HIGHS 10 TO 12.
PROBABILITY OF PRECIPITATION ZERO TODAY. ZERO TONIGHT. 30 PERCENT
SATURDAY.
WESTERN LAKE ONTARIO
NIAGARA REGIONS
HAMILTON
BRANTFORD CITIES.
SUNNY WITH CLOUDY PERIODS TODAY. BRISK EASTERLY WINDS GUSTING
TO 45 KMH. A FEW CLOUDS TONIGHT WITH LOWS NEAR PLUS 2. INCREASING
CLOUDINESS SATURDAY. CONTINUING WINDY. HIGHS 10 TO 12.
PROBABILITY OF PRECIPITATION ZERO TODAY. NEAR ZERO TONIGHT. 20
PERCENT SATURDAY.
NORTHERN LAKE HURON
SOUTHERN GEORGIAN BAY
EASTERN LAKE ONTARIO REGIONS
PETERBOROUGH CITY.
MAINLY SUNNY TODAY WITH BRISK EASTERLY WINDS. SATURDAY SUNNY
WITH CLOUDY PERIODS. LOWS TONIGHT NEAR FREEZING TO MINUS 3. HIGHS
SATURDAY NEAR 10.
PROBABILITY OF PRECIPITATION ZERO TODAY. ZERO TONIGHT. NEAR ZERO
SATURDAY.
END PART 1

FPCN50 CYYZ 210921
ONTARIO WEATHER OUTLOOK FOR SUNDAY THROUGH TUESDAY ISSUED BY
ENVIRONMENT CANADA AT 6.00 AM EDT FRIDAY OCTOBER 21 1983.
SOUTHERN ONTARIO
NORMAL LOWS NEAR 4...HIGHS 12 TO 14.
SUNDAY...RAIN. LOW 6 TO 9. HIGH 12 TO 15.
MONDAY...CLEARING AND MILDER. LOW 7 TO 10. HIGH 16 TO 19.
TUESDAY...CHANCE OF SHOWERS. LOW 9 TO 12. HIGH 16 TO 19.
CENTRAL ONTARIO
NORMAL LOWS NEAR 2...HIGHS NEAR 10.
SUNDAY...CHANCE OF SHOWERS. LOW 2 TO 5. HIGH 10 TO 13.
MONDAY...MAINLY SUNNY AND MILD. LOW 2 TO 5. HIGH 14 TO 17.
TUESDAY...CHANCE OF SHOWERS. LOW 5 TO 8. HIGH 13 TO 16.
NORTHERN ONTARIO
NORMAL LOWS NEAR MINUS 1...HIGHS NEAR 7.
SUNDAY AND MONDAY...MAINLY SUNNY AND MILD. LOWS FREEZING TO PLUS
3. HIGHS 14 TO 17.
TUESDAY...CHANCE OF SHOWERS AND TURNING COOLER. LOW 5 TO 8.
HIGH 10 TO 13.
END.

FICN1 CYYZ 211550
ONLY MINOR CHGS HV BEEN INCORPORATED IN LTST FCSTS AND 12Z PROG.
COMMENTS REGARDING COLD LO OVR KS THIS MRNG STILL APPLY AND LTST
CMC SPCTRL PROGS CONTINUE THIS TREND. SIG DIFFS BTWN LFM AND SPCTRL
PROGS ARE IN RELATIVE STRENGTH OF PRESS CNTRS. WE HV ADJUSTED
PRESS CNTRS TO BE MORE REALISTIC THAN SPCTRL WUD INDICATE. HNC
GRAD ACRS SRN AND CNTRL ONT WILL NOT BE QUITE AS STG AS THAT SHOWN
ON SPCTRL PROGS.
RAIN WILL MOV INTO SWRN ONT LT TONITE OR ERLY SAT MRNG. LFM QPF
SHOWS 10/15 MM RAIN YQG AREA BTWN 12Z AND 24Z SATWHICH SEEMS RSNBL.
LDG EDGE OF RAIN WILL CNTUE TO BE SLO MOVG AND NOT XPCTD TO RCH
S CNTRL AND SERN ONT TIL SAT NGT.
THRU NRN ONT AND CNTRL ONT ONLY WX IN NEXT 24-36 HRS WILL BE CLDS
AND OCNL SHWRS ASOCTD WITH SFC AND UPR TROF.
OTLKS SEEM RSNBL AT THIS TIME AND FLW QUITE WELL FM AVLBL 48 HR
PROGS.
NO WRNGS OR ADVSRYS IN EFFECT.
END/KEATING.

FACN2 CYYZ 211730
18-06
OTLK 06-18
HGTS ASL UNLESS NOTED
PROG
E-W QSTNRY RDG THRU EARLTON. TROF LN WINNIPEG-ISLAND LAKE AT 18Z
MOVG TO LN 30 W WINISK-60 W THUNDER BAY BY 06Z. RGNS IN LGT ACYC
FLO DRY STBL AMS XCP MDT SLY FLO NRN COCHRANE RGN. LGT-MDT SLY
FLO MOIST AMS WITHIN 200 E TROF
NRN COCHRANE RGN
CLDS AND WX. GNLLY CLR TO /SCT. WITHIN 300 E TROF 100 SCT OCNL
BKN 180 /SCT OCNL /BKN BCMG VCNTY AND WITHIN 250 E TROF 30-40
BKN V OVC LYRS 200 /OVC GVG OCNL 4-6R- AND ISOL ST CIGS 4-10 HND
WITH VSBY 3-5R-. SFC WND 2015G30 WITHIN 300 E TROF
ICG. LGT RIME ICGIC ABV FRLVL. FRLVL NR 60
TURBC MDT MECH DUE TO GUSTY SFC WNDS
OTLK...MVFR CIGS/R OCNL IFR CIGS/R
SUDBURY SUPERIOR SRN COCHRANE RGNS
CLDS AND WX. GNLLY CLR TO /SCT. LCL 30-40 SCT 60 MAINLY IN
FLO OFF LK SUPERIOR. VCNTY AND WITHIN 300 E TROF 30-40 SCT V
BKN 60 80 BKN PTCHS 150 /BKN
ICG. LGT RIME ICGIC ABV FRLVL. FRLVL NR 80
OTLK...VFR OCNL MVFR CIGS
END

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FXCN3 CWA05 211200
2519 27R1/0/0/0
2619 56R/29R1/0/0
2418 11R/0/0/0
2518 15R/0/0/0
2516 0/0/0/11R1
END

FXCN3 CWA04 211200
2320 0/0/0/3R
2420 0/0/0/3R
2319 0/0/0/14R1
2419 4R1/0/0/2R
2318 0/0/0/5R
END

FXCN3 CWA01200
2719 43R/3R/12R/0
2819 9R/0/0
2818 0/52/00
2714 0/0/0/2
ENB0200
2616 0/0/0/
2515 0/0/127R1/33
2615 0/0/0/1
2514 0/21R3360R2
2614 05R/1
END
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FOUS74 KWBC 260000
OUTPUT FROM LFM 00Z OCT 26 83
STA RH R1R2R3  VVLI HHDDFF TBPSPTT STA RH R1R2R3  VVLI HHDDFF TBPSPTT
YQB 39 634529 ///23 471409 7818/// YQM 51 636232 ///19 471911 8014///
 06 39 624229 00621 461405 7810000  06 63 757834 01916 422208 8011000
 12 51 625639 00519 430902 7908000  12 72 889130 00013 382710 7909000
 18 62 696947 01217 402805 7906000  18 83 969846 00811 333014 7810002
 24 77 788363 01015 363108 7805000  24 88 969666 00309 313017 7810000
 30 87 869178 00514 332914 7706001  30 91 949385 00109 293019 7712000
 36 95 969595 00613 303018 7607003  36 82 878474 00109 283020 7714002
 42 93 979293 00413 292921 7509005  42 59 736440 -0111 293021 7816000
 48 80 888271 -0313 293023 7611003  48 39 583925 -0712 322917 8019000
YMN 55 606539 ///20 461812 8014/// YYB 68 818046 ///14 413205 8113///
 06 69 738245 02516 412108 7911000  06 78 889443 01811 363016 8013000
 12 77 889440 00114 372708 7909000  12 80 919151 00010 323017 7913000
 18 89 999960 00911 323113 7810002  18 84 898775 00308 303216 7913000
 24 93 999779 00510 303116 7710001  24 83 858381 00208 283218 7814000
 30 93 969390 00310 283120 7712002  30 66 776950 -0209 283219 7817000
 36 79 868170 00310 273121 7714002  36 46 685121 -0511 303218 7817000
 42 54 715835 -0111 293021 7816000  42 38 573727 -0513 323114 8020000
 48 36 573524 -0613 322916 7918000  48 42 493353 -0615 372509 8119000
YLH 63 705764 ///10 282808 7715/// YQT 57 576150 ///12 332613 8017///
 06 64 685780 -0809 273008 7716000  06 62 576265 00310 332609 8016000
 12 57 705552 -0110 283412 7718000  12 58 606248 -0409 343416 8017000
 18 46 685120 -0712 293308 7718000  18 44 575118 -1511 353313 8020000
 24 46 634538 -0413 313105 7718000  24 45 534341 -0513 383305 8119000
 30 55 604669 00014 332108 7819000  30 53 494673 -0414 412108 8321000
 36 57 565071 -0315 372014 8015000  36 54 435069 -0415 472017 8516000
 42 63 496079 00515 421819 8211000  42 61 325693 01114 532019 8811000
 48 77 437993 00915 471822 8404000  48 48 235158 00713 592024 9304000
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FOCN02 CWA03 211620

STN : WG SPECTRAL DATA FROM OCT 21 83 12 0

		HOURS	0	6	12	18	24	36	48	60
THK		1000-500	550	551	552	551	551	554	556	551
		850-500	417	417	418	418	417	420	422	416
		850-700	157	157	157	157	157	158	159	157
Z	500		569	569	569	568	566	564	560	555
PCP				0	0	0	0	0	0	0
T	850		4	6	6	6	6	7	9	6
	700		-2	-1	-1	-1	-1	1	2	-2
DPD	1000		5	6	6	5	5	6	5	9
	850		7	8	9	11	11	13	14	8
	700		5	12	19	21	21	23	20	8
RH	850		61	57	51	46	44	39	35	55
	700		69	39	22	18	19	17	21	56
KI			14	15	0	-1	-1	-4	-3	15
DIV	850			-1	0	-1	3	1	-3	-4
	300			-6	2	2	1	-9	7	28
W	850			0	0	2	0	-1	-9	3
	700			3	1	-1	3	1	-3	-11
CLD	L			0	0	0	0	1	0	0
	MED			0	0	0	0	0	0	99
	HI			0	6	65	3	0	25	98
TMP	SFC	7	7	10	11	9	7	6	5	3	9	5	12
MSL		1022	1023	1022	1021	1021	1021	1020	1020	1018	1012	1005	1005
DIR	1000	198	200	213	211	203	210	217	217	199	166	177	274
SPD	1000	20	28	24	17	17	21	19	16	14	26	23	22

FOCN02 CWA02 211620

STN : YZ SPECTRAL DATA FROM OCT 21 83 12 0

		HOURS	0	6	12	18	24	36	48	60
THK		1000-500	547	549	550	551	551	556	563	563
		850-500	416	417	418	418	418	422	426	425
		850-700	156	156	157	157	157	159	160	161
Z	500		574	576	577	577	576	575	572	572
PCP				0	0	0	0	0	15	13
T	850		3	3	4	4	5	6	10	13
	700		-2	-1	-1	0	0	3	4	5
DPD	1000		10	7	5	5	4	5	4	5
	850		20	23	22	21	18	13	0	4
	700		22	25	27	27	24	13	0	13
RH	850		21	17	18	20	26	38	100	75
	700		17	13	11	11	14	38	100	39
KI			-17	-26	-23	-21	-15	0	31	24
DIV	850			-2	-5	-6	-4	-16	-22	0
	300			-6	-1	-1	-1	14	4	-8
W	850			3	2	2	-6	-8	0	-2
	700			3	1	0	2	-11	-15	1
CLD	L			0	4	2	0	16	100	29
	MED			0	0	0	0	13	100	0
	HI			0	0	0	0	23	90	0
TMP	SFC	1	6	10	10	9	8	7	7	6	12	14	19
MSL		1033	1034	1033	1032	1033	1033	1032	1032	1031	1023	1011	1010
DIR	1000	107	105	106	113	126	144	157	163	167	132	167	230
SPD	1000	16	19	20	21	20	35	37	38	38	49	49	33

WWCN1 CYYZ 120459
FREEZING RAIN WARNING FOR THE EASTERN ALGOMA NORTHERN GEORGIAN BAY HALIBURTON AND EASTERN LAKE ONTARIO REGIONS OF ONTARIO INCLUDING NORTH BAY AND SUDBURY CITIES ISSUED BY ENVIRONMENT CANADA AT 12.05 AM EST MONDAY DECEMBER 12 1983.
FREEZING RAIN HAS BEEN REPORTED OVER A LARGE AREA EXTENDING FROM JUST NORTH OF LAKE ONTARIO THROUGH TO THOSE REGIONS NORTH OF LAKE HURON AND GEORGIAN BAY.
THE FREEZING RAIN IS EXPECTED TO CONTINUE THROUGH THE NIGHT AND INTO MONDAY MORNING BEFORE CHANGING TO RAIN AS TEMPERATURES RISE ABOVE FREEZING.
THIS WARNING WILL BE UPDATED OR CANCELLED BY 7.00 AM EST THIS MORNING.
END/AMK

C 2

WWCN1 CYYZ 121102
UPDATED FREEZING RAIN WARNING FOR THE EASTERN ALGOMA NORTHERN GEORGIAN BAY HALIBURTON AND EASTERN LAKE ONTARIO REGIONS OF ONTARIO INCLUDING PETERBOROUGH NORTH BAY AND SUDBURY CITIES ISSUED BY ENVIRONMENT CANADA AT 6.10 AM EST MONDAY DECEMBER 12 1983.
FREEZING RAIN WILL CONTINUE THIS MORNING OVER A LARGE AREA EXTENDING FROM JUST NORTH OF LAKE ONTARIO THROUGH TO THOSE REGIONS NORTH OF LAKE HURON AND GEORGIAN BAY.
THE FREEZING RAIN WILL GRADUALLY COME TO AN END DURING THE MORNING AS TEMPERATURES RISE ABOVE FREEZING.
THIS WARNING WILL BE UPDATED OR CANCELLED BY 11.00 AM EST THIS MORNING.
END/AMK

WWCN1 CYYZ 121450
CANCELLATION OF FREEZING RAIN WARNING FOR THE EASTERN LAKE ONTARIO EASTERN ALGOMA AND NORTHERN GEORGIAN BAY REGIONS INCLUDING PETERBOROUGH SUDBURY AND NORTH BAY CITIES ISSUED BY ENVIRONMENT CANADA AT 9.45 AM EST MONDAY DECEMBER 12 1983.
FREEZING RAIN HAS CHANGED TO RAIN IN THE EASTERN LAKE ONTARIO REGION WHERE TEMPERATURES HAVE CLIMBED ABOVE FREEZING. ACROSS THE NORTHERN GEORGIAN BAY AND EASTERN ALGOMA REGIONS PRECIPITATION HAS BEEN FALLING AS A MIXTURE OF SNOW AND ICE PELLETS. THE FREEZING RAIN WARNING FOR THE ABOVE REGIONS IS HEREBY CANCELLED.
A FREEZING RAIN WARNING REMAINS IN EFFECT FOR THE HALIBURTON REGION AND WILL BE UPDATED OR CANCELLED BY 3.00 PM EST TODAY.
END/EHR

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SACN1 CYHZ 271300
YFC SA 1300 E100 OVC 15 040/1/-2/2305/964/AC9 =
YYG SA 1300 12 SCT 80 SCT 15 024/5/1/2410/959/SC1AC3 =
YQY SA 1300 10 SCT M32 BKN 15 045/7/6/2009/966/SF3SC5 =
YQI RS 1300 E12 BKN 15 047/9/6/2611/967/TCU8 SHWR SW =
YHZ SA 1300 M26 BKN 15 052/5/2/2207/967/SC9 =
YCL SA 1300 E20 BKN 40 OVC 6S- 996/1/0/2406/951/SC6SC4 =


SACN1 CYSB 271300
WNZ SA 1300 AUTO2 CLR BLO 100 9.+    117/ 02/ 01/2409/-/0002 6016
 =
YXZ SA 1300 18 SCT E33 OVC 15R-- 139/4/0/1607/990/SC2SC8 =
YLD RS 1300 SAWR B13 BKN 100 BKN 15 M/-1/-3/2104/995/=
YMO SA 1300 SAWR 40 SCT 200BKN 10 M/-4/-8/1805/988/=
YYU SA 1300 E100 BKN 240 OVC 15+ 128/-1/-2/1804/987/AC8CI2 =
YTS SA 1300 E100 BKN 220 OVC 15 145/-3/-4/2002/991/AS8CI2 =
YEL SA 1300 SAWR 30 SCT E100BKN 15 M/-2/-3/0000/001/=
YZE SA 1300 20 SCT 100 -SCT 140 -BKN 15 172/1/-1/0000/002/SC1AS1AC3
=
WBI SA 1300 AUTO2 MMMM 9.+  180/-03/-03/MM05/-/ 2004 =
YSB SA 1300 E220 OVC 15 165/-1/-3/2802/996/CS7 FROIN =
YXR SA 1300 140 SCT 230 -SCT 15 156/-3/-4/2603/995/AC2CI =
YVO SA 1300 M6 OVC 15 143/-2/-3/3205/990/SF10 =
YUY SA 1300 -X B3 OVC 1/2F 155/-2/-2/3002/994/F5SF5 =
YMT SA 1300 9 SCT E12 OVC 12 091/-1/-4/3206/975/SF1SC10 ?
YNM SA 1300 6 SCT E12 OVC 8 134/-1/-2/2706/988/SF1SC9 =
YGL SA 1300 E30 OVC 15+ 107/-2/-9/0000/980/SC10 =
YAD SA 1300 SAWR A15 BKN 50 BKN 15 M/-2/-6/3404/980/=
YAH SA 1300 SAWR -X E15 BKN 30 OVC 5S- M/-1/-4/3605/970/=
YGQ SA 1300 E120 BKN 15 070/5/3/1808615/969/AC9
VIRGA OVHD ACC ASOCTD PRESFR =


SACN1 CYUL 271300
YWA SA 1300 30 SCT 15 142/1/-2/3011/994/SC3 =
YND SA 1300 E18 BKN 40 BKN 15 103/4/3/3012/983/SC8SC1 =
YOW SA COR 1300 12 SCT M16 OVC 25RW-- 114/4/2/2910/985/CF2SC8 =
YHU SA 1300 15 SCT E40 BKN 100 OVC 15RW-- 084/5/3/2808/977
/SF2SC6AC2 =
WOH SA 1300 B9 BKN 20 OVC 10 090/2/2/3109/975/SC6SC4 =
YUL SA 1300 7 SCT 20 SCT E50 BKN 15 090/5/4/2808/979/SF1SC3SC4
 =
YMX SA 1300 6 SCT M38 BKN 100 BKN 210 BKN 15 092/4/3/2404/979/
SF1SC6AC2CI1 =
WXF SA 1300 AUTO1 E3 BKN 7 BKN     093/ 02/ 02/2804/-/     2017
 =
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2119 YVV SA 1900 CLR 15+ 328/11/2/1008/048/ =
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SXCN2 CYYZ 211200
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SOG IN CENTIMETRES
IF PCPN NIL 12Z SOG USED

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YXL	11	2	NIL	
WIB	11	M 5	NIL	
WYW	MM	M 2	MM	
YGQ	10	M 6	NIL	2
YMO	9	M 1	NIL	
YYU	10	M 3	NIL	
YVO	5	M 7	NIL	
YXR	7	M 7	NIL	
YXZ	10	M 6	NIL	
YAM	10	M 1	NIL	
YZE	9	1	NIL	
YWA	8	M 8	NIL	
YPQ	9	M 3	NIL	
YGK	8	M 1	NIL	
YTR	9	M 3	NIL	
YOA	10	M 2	NIL	
YVV	8	1	NIL	
WLS	8	M 1	NIL	
WTO	9	2	NIL	
YHM	8	2	NIL	
YSN	12	0	NIL	
WSI	11	3	NIL	
YKF	8	1	NIL	
ALB	10	M 3	NIL	
YZR	12	4	NIL	
ROC	12	M 2	NIL	
SYR	11	M 4	NIL	

SXCN1 CYYZ 211800
PCPN IN TENTHS OF MILLIMETRES
SOG IN CENTIMETRES
IF PCPN NIL 12Z SOG USED

	12HR MAX	24HR MIN	6HR PCPN	SOG
YQK	8	5	NIL	
YQT	10	M 5	NIL	
YTS	10	M 6	NIL	
YSB	9	M 2	NIL	
YYB	7	M 1	NIL	
YUL	7	M 2	NIL	
YOW	8	M 3	NIL	
YYZ	10	M 1	NIL	
YXU	13	0	NIL	
YQG	14	7	NIL	
BUF	14	M 1	NIL	
BOS	8	2	NIL	
TEB	12	4	NIL	
CLE	15	9	NIL	
PIT	12	7	NIL	
DCA	13	9	NIL	
MIA	30	23	TR	
JAX	23	20	TR	
ATL	17	14	NIL	
MSY	29	21	NIL	
HOU	25	18	TR	
DFW	17	14	NIL	
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STL	16	12	0080	
MCI	10	8	0005	
DEN	16	0	NIL	
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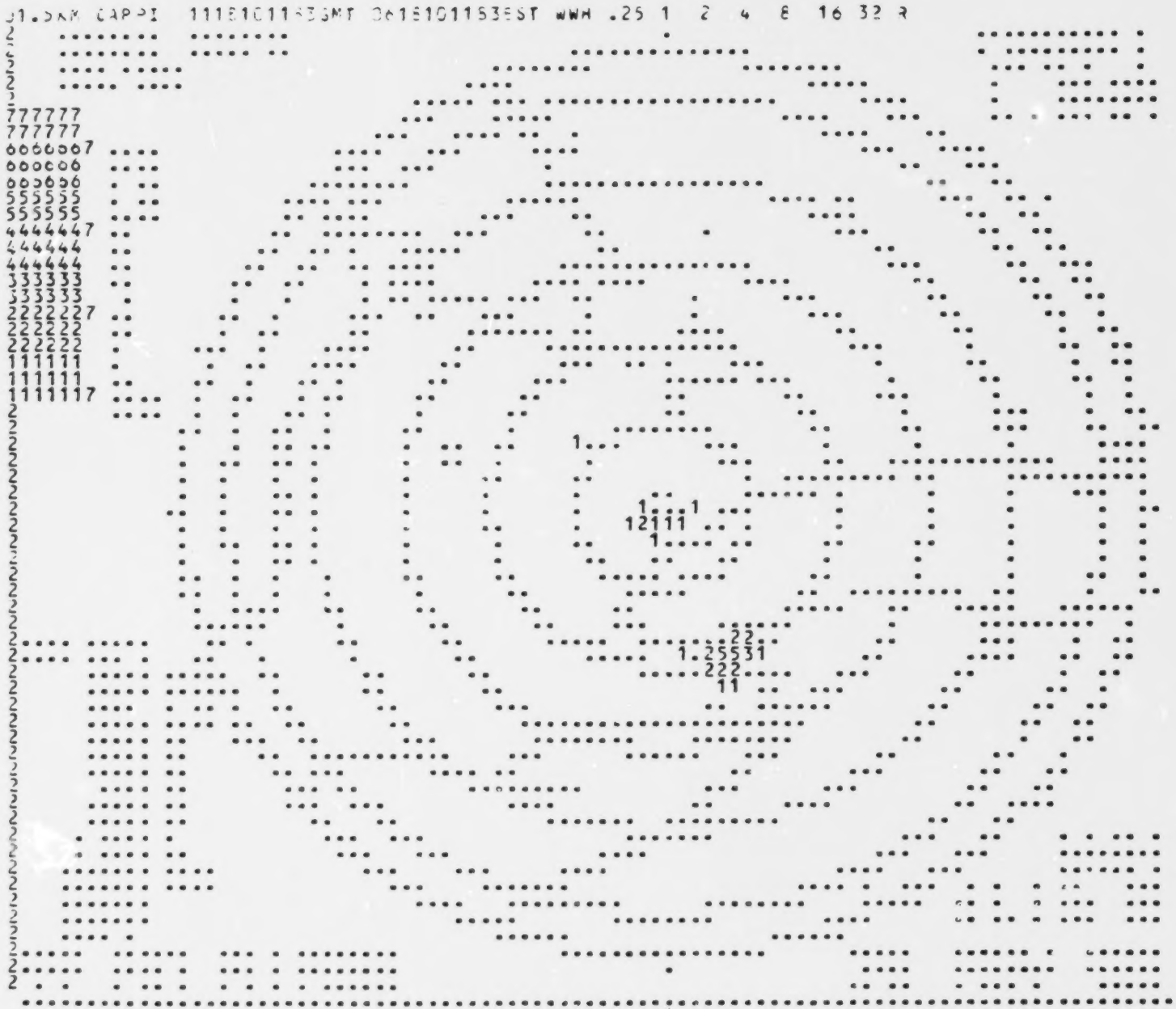
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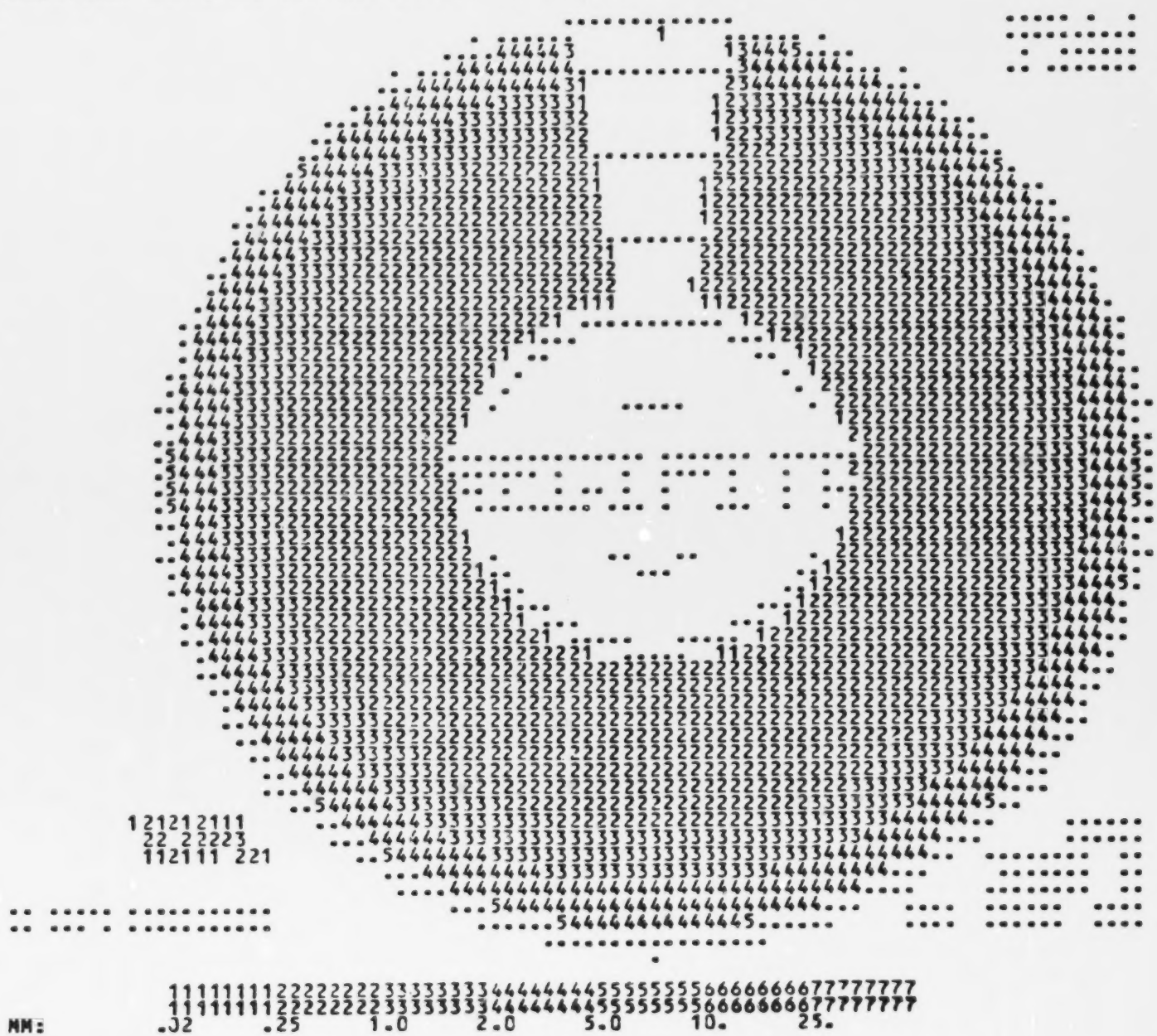
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MINUTES,NUMBER OF CAPPIS: 331 27
GRADATIONS (MM): .02 .25 1.0 2.0 5.0 10. 25. X1
MM: .02 .25 1.0 2.0 5.0 10. 25.

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?
TYPE P$MACROS
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THIS IS A LIST OF THE PLOTTING MACROS CURRENTLY AVAILABLE

PR06	PLOTS 6-HR AND 24-HR PRECIPITATION DATA ON THE SAME GRAPH. DEFAULT STN=YVV; TIME=72 HRS FROM PRESENT;MAX=35 MM; MIN=0 MM
PR06.$L	AS ABOVE, EXCEPT THAT OUTPUT IS TO $LPT; DEFAULT TIME=168 HOURS FROM PRESENT
PR06.$C	AS ABOVE, EXCEPT THAT OUTPUT IS TO CD, AND DEFAULT NUMBER OF HOURS IS 48.
STREAM	GIVES THREE GRAPHS OF FLOW,TEMP, AND 6-HR PRECIP; DEFAULT STN= 4540F914, AND TIME IS 72 HOURS FROM PRESENT.
TEMP./$L/$C/$W	OUTPUTS TEMPERATURE; DEFAULT STN=YVV, TIME 72 HRS FROM PRESENT
TEMPALL.$L	OUTPUTS GRAPHS OF TEMPERATURE DATA TO THE $LPT FOR THE FOLLOWING STATIONS YVV,YYZ, YUL AND SOUTHERN ONT.
LEVL./$L	WATER LEVEL DATA DEFAULT STN=4540F914; AND TIME 72 HRS FROM PRESENT, IN CENTIMETERS.
FLOW./$L/$C	STREAMFLOW FOR 4550F914.
WTMPDCP./$L	GIVES 72 HOURS OF WATER TEMP FOR ALL APPLICABLE DCP'S.
PRECDCP./$L	GIVES 72 HOURS OF PREC DATA FOR 9 DCP'S.
DCPDATA./$L	FLOW, TEMPERATURE AND SIX-HR PRECIP
STREAMDCP.$L	WATER LEVEL AND FLOW
PR06AES.$L	PRECIP
TEMPNO.$L	PLOTS TEMPERATURE FOR NORTHERN ONT. STATIONS (108 HOURS)
TEMPNW.$L	PLOTS TEMPERATURE FOR NORTHWESTERN ONT. STATIONS (108 HOURS)

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PLT TEMP YYZ
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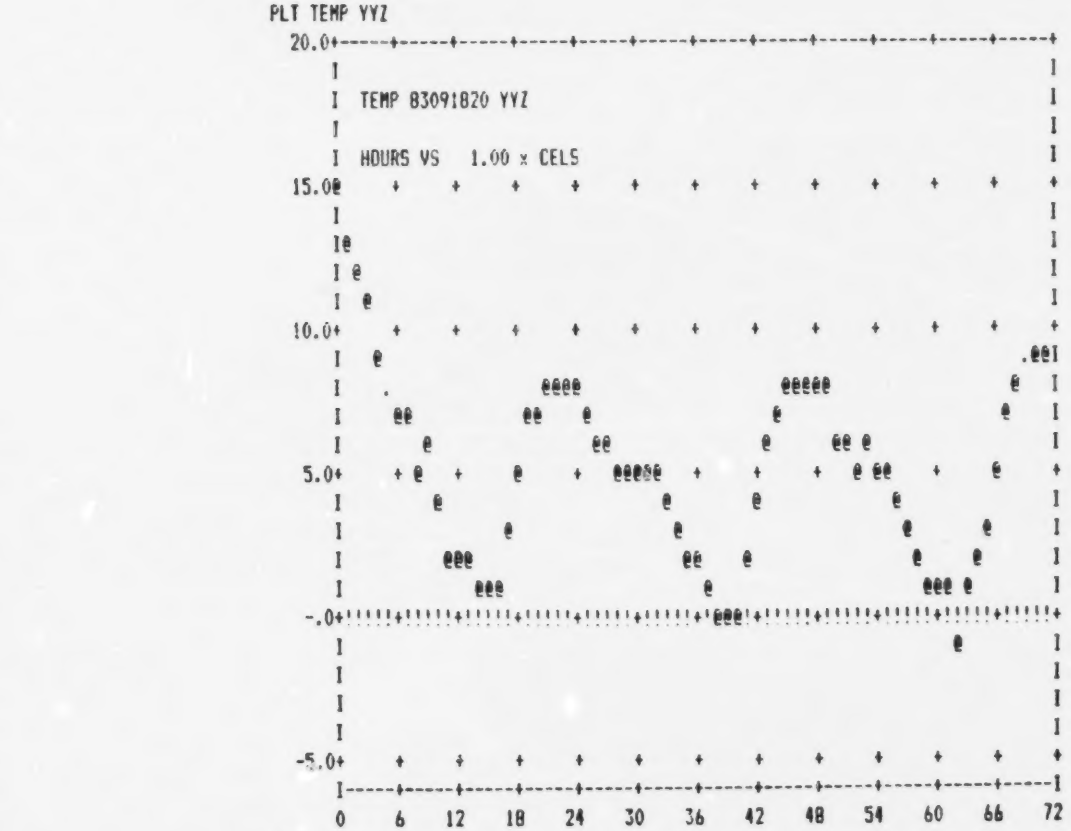


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TRENT-SEVERN WATERWAY FORECASTING

Background Paper for Workshop

AES Downsview

November 22-24, 1983

by: B.W. Kitchen

August 31, 1983

TRENT-SEVERN WATERWAY FORECASTING

BACKGROUND PAPER FOR WORKSHOP

NOVEMBER 22-24, 1983

BY B.W. KITCHEN

INTRODUCTION

Description of Waterway:

The Trent-Severn Waterway is a 386 kilometre inland waterway which crosses Ontario from Trenton on the Bay of Quinte to Port Severn on Georgian Bay by connecting together natural rivers and lakes in two watersheds.

The easterly Trent watershed has an area of about 11,400 square kilometres with about 40 reservoir lakes on the Gull, Burnt, Nogies, Mississagua, Eels and Jack Creek watersheds. The reservoir water is used to maintain navigation depths on all the lakes and river reaches from Balsam Lake down to Trenton, and is used to maintain water quality, and to supply power at 17 generating stations.

The westerly Severn watershed, with an area of about 7,250 square kilometres, is a much less complex watershed to manage. The only operational reservoir on this system is Lake Simcoe-Couchiching, which is allowed to drop about 40 centimetres over the summer and fall in order to provide a flow in the Severn River. This flow ensures the maintenance of navigation levels, water quality in the river and some water for power generation at 2 permanent generating stations.

Forecasting Needs:

The major requirement for forecasting for the two watersheds on the canal route is for the seasonal supply of water. Flooding events do occur and

are mitigated to some extent, but the emphasis of the operation has always been to provide water for navigation, recreation, power production, municipal uses, etc. Agricultural interests have to be considered as well, especially when affected by flood levels such as occurs in the Holland Marsh area at the south end of Simcoe.

The lake systems in their original state were not designed to control floods and today only in Haliburton Highlands are the lake volumes any appreciable mount larger than in their original state. The Kawarthas and Simcoe-Couchiching lakes often fill to their proper full levels even with their control dams wide open. Flooding is modified to some extent by the usual slow rate of runoff from the basins feeding these lakes.

The storage capacity and hence the operating strategy is divided into three major geographical areas. Farthest north in the Trent watershed are the Haliburton Reservoirs. South of them at the ends of the tributary rivers is the Kawartha Lakes area which receives their inflow and discharges to the Trent River via the Otonabee River and Rice Lake. The third storage area is Lake Simcoe-Couchiching, the only operational storage reservoir for the Severn watershed.

PART I

Historical Attempts:

For Lake Simcoe-Couchiching in 1965 the Meterological Branch of Department of Transport attempted to predict the rise in level of the lakes for

March-April and for May based on late-winter, early spring conditions. Precipitation values came from four climat stations around the lake with their data distributed on the watershed by the Thiessen Polygon method. Snow data came from six snow courses around the lakes. Water level data came from three gauge sites on the lake and outflow figures came from records computed for Washago. Start of breakup was determined from the initial rise of the largely uncontrolled Black River at Washago.

Regression equations were calculated by least square methods to relate lake level changes to snow surveys or to precipitation using data for years 1955-64. Attempts were made both including and excluding a 30-day weather (precipitation) outlook prepared by the U.S. Weather Bureau. Inclusion of this outlook did not seem to help the accuracy of prediction and the project reporter advised that the correlations using the outlook not be used.

It was also determined that the change in lake level in May did not have a definite relationship with precipitation falling in the winter or previous fall. It tended to only relate to precipitation occurring in May itself.

Recommended forecast equations were:

(i) End of February

$$EF = 0.21\ P_F + 0.16\ P_{DJF} - 0.68$$

(ii) End of March

$$EM = 0.17\ P_F + 0.24\ P_W + 0.27\ P_M - 1.47$$

(iii) First of May - Using a 30-day outlook

ΔL_m = 0.51 if outlook says above normal

= 0.34 if outlook says normal

= 0.24 if outlook says below normal

Where : EF = Forecast rise inlake level (ft) (end of February forecast)

EM = Forecast rise in lake level (ft) (end of March forecast)

P_F = Prec. (ins.) in February

P_{DFJ} = Prec. (ins.) in Dec. Jan. Feb.

P_w = Prec. (ins.) in winter (Dec. Jan. Feb.) plus that in March and April falling before the rise begins

P_m = Prec. (ins.) in March falling after the rise begins

ΔL_m = change in level (ft) in May

Quite good correlation coefficients were achieved for both relationships. This method was computed on a trial basis for several years while the Trent-Severn Waterway (then Trent Canal) collected data and hoped for some refinements due to additional data and method improvement. With changes in both agencies the project did not proceed much further. It probably still holds promise for renewed effort in this regard.

Another method of snowmelt forecast (estimation) was also performed for several years, but proved to be quite unreliable. It was based on snow

accumulation alone at five sites around Lake Simcoe-Couchiching and three sites around Scugog Lake. Considering that the Met Branch (now Atmospheric Environment Service) discovered no help was achieved from use of snow data, it is not hard to see why this approach was dropped.

PART II

Consultant Recommended Procedures:

Scope:

In 1972 a private consulting company was commissioned to analyze the water control operations and procedures on the Trent River system and recommend improvements. The major result of this was a reservoir routing procedure most useful in summer reservoir drawdown periods. As a side issue, however, a multiple linear regression of spring season water supply was made, related to snow on the ground in the Haliburton Area. This procedure was to predict the total inflow to the watershed upstream of Lakefield where the Otonabee River leaves the Kawartha Lakes between March 15th and May 15th.

Preparation:

The operator would make a calculation on each of February 1, February 15 and March 1 using the established correlations with snow data from six Ontario Ministry of Natural Resources and two Ontario Hydro snow courses.

The consultants procedure was to provide spring inflow forecasts for a two month period (March 15 to May 15) at six, four, and two weeks prior to its beginning. No meteorological forecasts are used in this procedure.

The Trent-Severn Waterway was advised to begin a snow survey program in the area and sites were recommended. The recommended snow survey sites were established yielding eight years of record to date for which an improved correlation may soon be possible. These snow course readings are made manually each two weeks from the beginning of January until the snow melts. Flow measurement information is not used in making these forecasts.

The Trent-Severn Waterway has no experience other than superficial (obtained during Water Survey efforts with the DCP and acoustic flowmeter at Wasdell Falls) with sophisticated flow measuring devices; none with satellite imagery.

Other aids developed by the consultant included a mass curve for the Otonabee River, on which the forecast would be marked (see Fig. 1). The plotted accumulation of the inflow was to begin March 15 heading toward the predicted inflow volume. As well as the mass curve a second graph was prepared (see Fig. 1) which employed guidelines of 8000 cfs (226 m^3/s) and 1000 cfs (28.3 m^3/s) to be drawn converging at the target volume of all the lakes above Lakefield. A curve then was projected down between these two lines beginning with the forecast and subtracting each day's outflow as time progressed toward the target at May 15. The appropriate amount of stored water for May 15 was to be selected ahead of time based on consequences of flooding or shortage. By monitoring the shape of this the operator was supposed to be able to gauge whether the freshet flow was being impounded too quickly or not quickly enough. It was also to give some guidance as to the likelihood of a superabundance which should be started out of the system as early as detection allowed.

Inflows were to be computed and graphed throughout the two month inflow period and as often as three times per week for a few weeks at the peak of the inflow time. This would help the operator stay abreast of the rapidly changing conditions. Instructions would be based on the rate of fill, expected precipitation and temperature, and lateness of the date. Advice on placing more or removing some stoplogs would be given to the water control crews the morning after each reading.

Routing:

As part of the assignment the consultant produced a mathematical simulation which optimizes an objective function of the reservoir system to assess the impact of alternative policies. An elaborate optimization model was believed to be not particularly useful for such a large multi-reservoir system due to computation cost and the desired level of detail envisaged. The derived simulation is now used operationally to select the proper flow of water at each dam and gauge site to satisfy the chosen policy and established constraints. This serves as a routing method in low inflow times and could be so used in high inflow times if reliable week-by-week inflow forecasts were available. The consultant stated that a further study on forecasting inflows to the system was warranted.

No backwater routine is included in the model and the flow relationships and time-lags for connecting channels are not calculated either. Each reservoir is assumed to pour directly into the one downstream which is generally the

case for about 75% of the lakes. Time-lags do cause some difficulty in the computation and the use of the recommended flows. In the approximately 25 of longer connecting channels the flows are still pouring into the downstream lake for several days after being cut back at the up-stream lake. This problem has been partially countered by setting a minimum acceptable flow along the affected reaches. It should be noted too that even improved calculation ability would not help without improved forecasting capabilities, because large flows being drawn for evaporation replacement are not known to be excessive until after the results of a heavy rain are felt. We dare not reduce the flow three days before a forecasted rain only to have the rain not arrive or not make any significant change to lake levels.

The simulation is not used during ice conditions and of course has no ice-jam capability.

Review of Performance:

The seasonal forecast procedure discussed earlier has been computed each spring from 1974 to 1983 (see Table 1). The ten years of results indicate that in years with plenty of snowfall and a late spring break-up the predictions were within 15% of the actual. However, this occurred only three times out of the ten years. Other years such as 1980 and 1983 which had little snow had errors of about -50%, while early breakups such as in 1981 produced errors of about +30%. Part of the trouble seems to be the use of a specified calendar date (March 15) for the beginning of the freshet. In early breakup years much of the spring inflow has

gone by March 15 and is therefore not included in the period predicted. Years with lack of snow cover are badly handled, because rainfall which can be large is not included or accounted for.

The mass curve and other aids did not seem to be guiding our decisions as much as we had hoped either. Often we could tell when to change fill rates, etc. by other observations, etc. before the results were drawn on the graphs. In the present operation we are guided mostly by the filling slope of the annual storage-depletion curve which we can compare to earlier years and conditions visually as well as by numbers.

Organization:

Trent-Severn Waterway is organized with a central office and four sub-offices. Calculations of expected inflow are made at the central (Headquarters) office and regular meetings are held as spring approaches with all sub-offices represented to discuss the expectations and talk over the probable course of action required.

Communications:

The flow and level situation is continuously monitored by the Water Control Engineer and based on the evident trends and possible precipitation recommended changes are telephoned to the sub-offices during regular daily communications. Several other agencies including Ontario Hydro, Peterborough

P.U.C., Campbellford P.U.C., and Orillia Water Light and Power Commission are also contacted daily by the Trent-Severn Waterway. These agencies as well as Conservation Authorities and Ontario Ministry of Natural Resources District Offices are invited to attend freshet planning meetings mentioned above to learn of the most up-to-date anticipations of the Trent-Severn.

When threatening situations are judged to be likely to occur, press releases are issued to radio and T.V. stations, and newspapers (often via wire service). These media often will then telephone to have an interview to expand the story for their listeners and/or subscribers.

PART III

Present Efforts:

The spring seasons of 1980 and 1981 were so far from normal and their resulting inflows so poorly predicted by the consultants methods that we began to question the value of doing the calculations. It seemed that the orderly years like 1978 and 1979 that were not problems were the only ones for which the method was accurate. Extreme situations which occurred could not be handled by the method and we were left with no guidance other than past records.

Consequently we began to look more closely at the previously recorded extremes to see what might be approaching us. In a manner similar to that used by AES in their Temperature Anomaly Forecast, we tried to detect other years whose characteristics for the recent past and present time spans were similar to the current year, then see how they turned out. I understand approaches

such as this have been computerized by some agencies to aid in their flow management efforts. We have not of course reached the stage of programming such a method but are interested in following it up with those who have tried it to see what their results have been.

Other calculations based on snow surveys and existing water levels, at least for Lake Simcoe-Couchiching have not been very promising. As a basis for the spring freshet meetings held at Trent-Severn Waterway Headquarters a couple of these calculations are made and some similar years compared to help determine in an open discussion a consensus of the best changes to make under the circumstances. A representative from each agency present is asked to summarize observations on snow, lake levels, flows, etc. in his respective area and these are discussed briefly. The meetings close with each respective area knowing approximately what to look for and what changes are likely to be needed before the next meeting, usually in two weeks.

In contacts with the media we are often asked the time and height of the crest in various areas such as Peterborough on the Otonabee. Though nothing formal has been prepared on this we can generally anticipate ahead of the peak as it appears and give them some idea within a day or two and also some expectation of its probable extreme height.

Conclusion:

Trent-Severn Waterway is very interested in seasonal supply forecasts. Our experiences may be similar to that of other agencies and we look forward to hearing about their efforts.

We are especially interested in the experience of others when using previous historical records to better assess the future happenings given any set of preceding conditions. We feel that our many years of record which include the extreme events could be used more effectively in this manner.

Another avenue of research which would materially assist us is in the improvement of long range weather forecasts. Runoff to be expected from such precipitation could probably be correlated (as done for Lake Simcoe-Couchiching in 1965) and such calculated inflows then used as input to the simulation model already in use at Trent-Severn.

APPENDIX

FIGURE 1

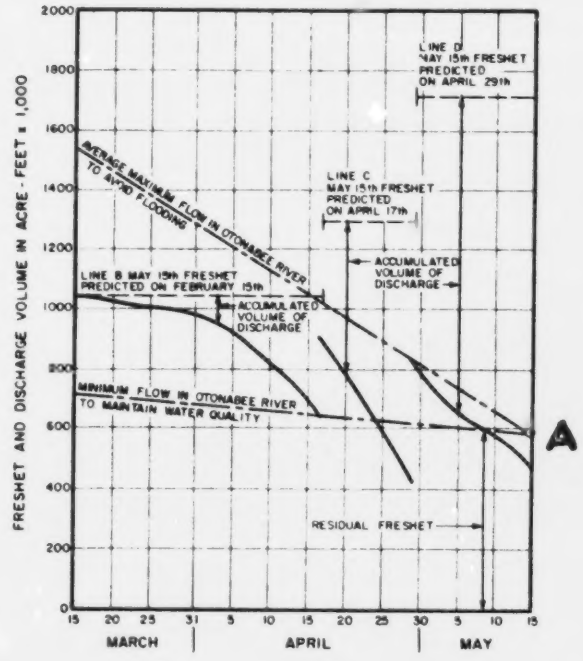

CHART I

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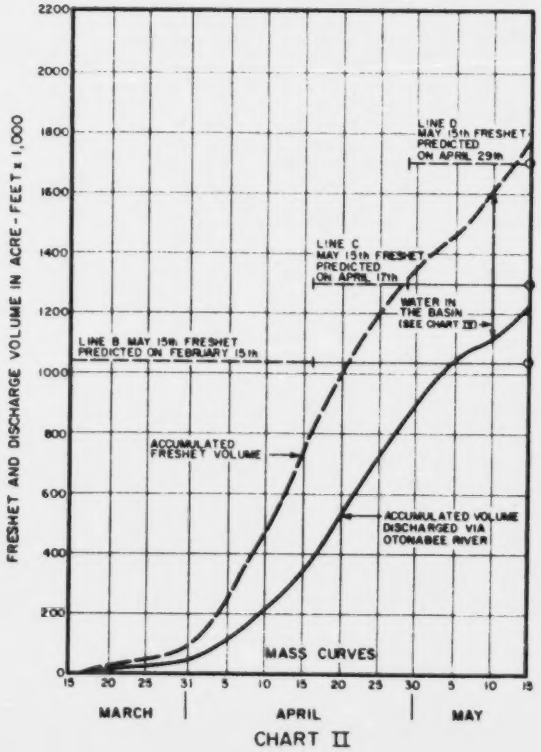

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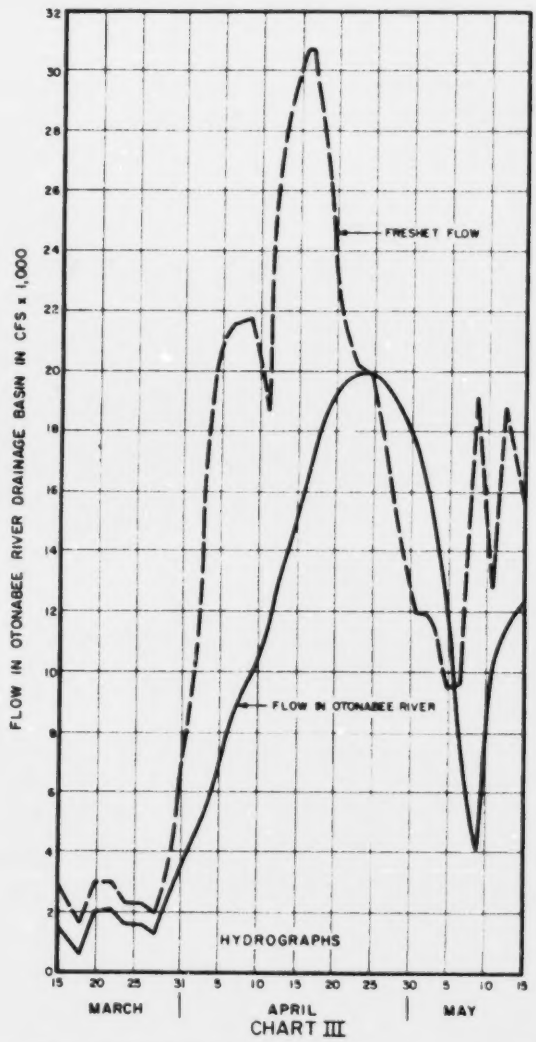

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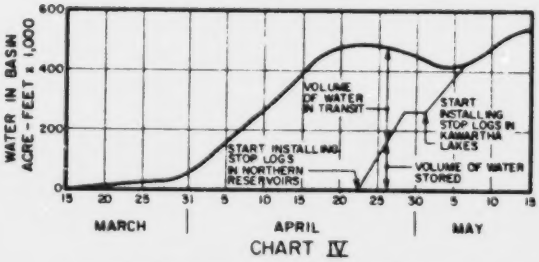

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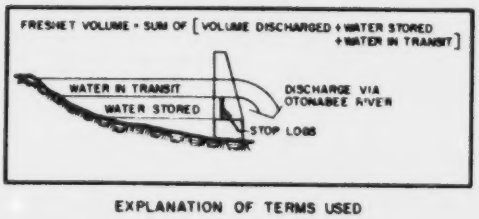


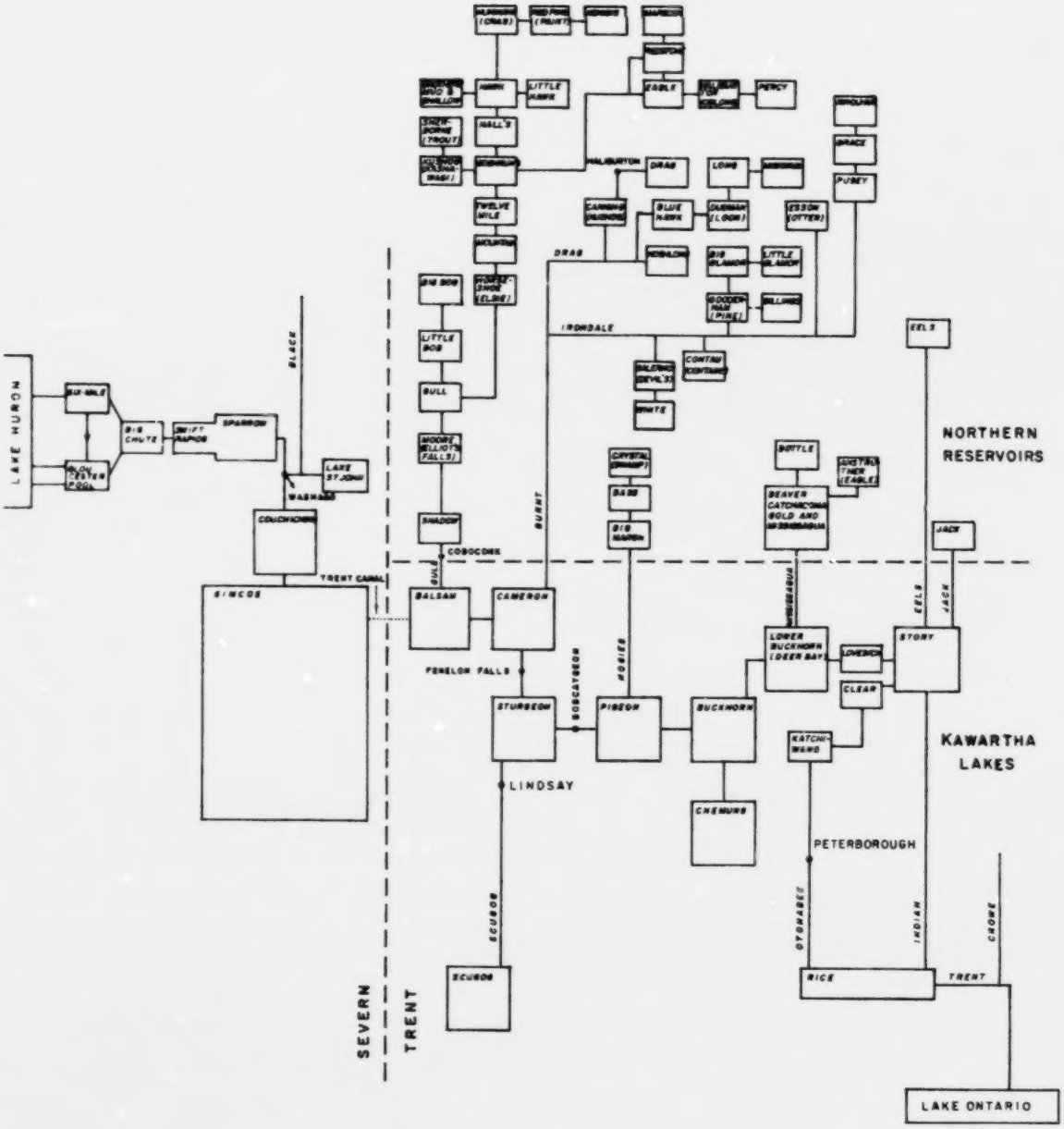
EXPLANATION OF TERMS USED

OTONABEE WATERSHED - FRESHET FORECAST RESULTS

TABLE I

YEAR	DATE	FORECAST Total Inflow - Mar. 15 May 15		ACTUAL	ERROR	% ERROR
			Average			
1974	Feb. 1	104,972				
	Feb. 15	104,848	104,269	136,853	-32,584	-31.2%
	Mar. 1	102,987				
1975	Feb. 1	82,065				
	Feb. 15	102,381	94,703	156,863	-62,160	-65.6%
	Mar. 1	99,664				
1976	Feb. 1	93,518				
	Feb. 15	113,621	110,821	165,614	-54,793	-49.4%
	Mar. 1	125,324				
1977	Feb. 1	124,065				
	Feb. 15	125,549	118,641	88,260	+30,381	+25.6%
	Mar. 1	106,309				
1978	Feb. 1	150,787				
	Feb. 15	126,114	128,696	142,193	-13,497	-10.5%
	Mar. 1	109,188				
1979	Feb. 1	147,514				
	Feb. 15	145,072	136,619	154,321	-17,702	-13.0%
	Mar. 1	117,272				
1980	Feb. 1	80,428				
	Feb. 15	79,506	78,042	120,036	-41,994	-53.8%
	Mar. 1	74,193				
1981	Feb. 1	122,777				
	Feb. 15	128,724	102,076	69,597	+32,479	+31.8%
	Mar. 1	54,726				
1982	Feb. 1	134,373				
	Feb. 15	129,531	130,640	142,166	-11,526	-8.8%
	Mar. 1	128,015				
1983	Feb. 1	82,065				
	Feb. 15	77,481	73,022	105,278	-32,256	-44.2%
	Mar. 1	59,520				

TRENT-SEVERN WATERWAY
LOCATION PLAN
PLATE I



TRENT-SEVERN WATERWAY
SCHEMATIC DIAGRAM

TSW 3077-8

GRAND RIVER CONSERVATION AUTHORITY

FLOOD FORECASTING FOR THE GRAND RIVER BASIN

Lorrie Minshall, P.Eng.,
Hydrological Engineer

1.0 BACKGROUND

1.1 The Grand River Watershed

The Grand River Basin covers approximately 6700 square kilometres of Southwestern Ontario. The basin stretches from Dundalk in the north to Lake Erie in the south, and from Stratford on the west to Georgetown on the east, as shown in Figure 1.

The river system is made up of five main streams, and a host of minor tributaries. The Grand River itself is the main stem of the system. Draining the western portion of the basin are the Conestogo River and Nith River which enter the main stream at the former Village of Conestogo and Paris respectively. The eastern section is drained by the Speed River which enters the Grand in Cambridge (Preston), and its tributary, the Eramosa River, which enters the Speed River at Guelph.

As with any river system, the Grand has a long history of floods. Severe floods have struck all municipalities along the rivers within the last 25 years. On the Grand River damage has occurred in Dunnville, Caledonia, Brantford, Paris, Cambridge, Kitchener, and Grand Valley; on the Nith River in Paris, Canning, Plattsville, Ayr, and New Hamburg; and on the Conestogo River in St. Jacobs and Drayton. On the Speed River, flood damage has been experienced in Cambridge and Guelph; the Eramosa River has flooded parts of Rockwood and Guelph. In May of 1974 several million dollars damage was done on the Grand. Floods of similar magnitude occurred in 1954, 1948, 1929 and many times in the past.

The City of Brantford takes water from the Grand River for water supply. While the City of Kitchener obtains most of its water supply from groundwater, they are now inducing infiltration into wells bordering on the Grand River and are looking at the feasibility of artificially recharging groundwater aquifers from the Grand River. In addition all of the communities on the Grand River and its larger tributaries discharge sewage effluent into the river.

1.2 The Grand River Conservation Authority

The Grand River Conservation Authority is a corporate body established under the Conservation Authorities Act of Ontario to manage watershed resources and related conservation projects in partnership with its member municipalities and the Province.

Figure 1

The Authority's regular staff number 115. The Water Management Division Engineering Section, whose responsibilities include water control operations and flood forecasting, is made up of four engineers and four technologists.

1.3 Multi-Purpose Reservoirs

In order to alleviate the recurrent flood threat, as well as other water management problems, the Grand River Conservation Commission and later the Grand River Conservation Authority have built three large dams: Shand Dam on the Grand River above Fergus, Conestogo Dam on the Conestogo River below Drayton, and Guelph Dam on the Speed River above Guelph. These dams provide a total storage of approximately 150 million cubic metres. This storage is available to impound the spring runoff. However, for a period in May and June, the available storage is reduced to approximately 10 million cubic metres. As low flow augmentation releases are made over the summer and fall, flood control storage is generated, reaching its maximum in time for the next spring runoff.

Table 1 Major Multipurpose Reservoirs in the Grand River Watershed

Dam	Drainage Area (km2)	Controlled Head (m)	Storage at Full Pool (106m3)	Storage at Full Pool (mm runoff)	Year of Construction
Shand	800	21.1	63.9	80	1942
Conestogo	570	21.6	59.5	104	1958
Guelph	240	12.8	22.4	93	1975

The reservoir storage is about half that required for a reasonable degree of flood protection. The multi-purpose nature of their operation means that storage available for flood control is reduced for a portion of the year. The travel times of discharge from the reservoirs to the flood damage centres are about equal for all three reservoirs. Therefore, the reservoirs must be operated in system; timing and magnitude of discharges become of extreme importance.

Augmentation of river flows is required during summer months to ensure adequate waste assimilation capabilities. Minimum flow rates have been established at Kitchener, Brantford, and Guelph to be maintained with augmentation from the reservoirs. Between May and October, augmentation is often fifty percent of the flow and may reach eighty percent for short periods of time.

The Authority also operates four smaller multipurpose reservoirs for local water control. These are: Luther Dam off the Grand River above Grand Valley, Woolwich Dam on Canagagigue Creek above Elmira, Laurel Creek Dam on Laurel Creek in Waterloo, and Shades Mill Dam on Galt Creek in Cambridge.

2.0 FLOOD FORECASTING

River and reservoir monitoring is required on a year-round basis to operate the reservoirs effectively for both flood control and low flow augmentation.

The aim of the flood forecasting system is two-fold: to quantify river levels in order to most effectively operate reservoirs to reduce flood levels; and to provide as much information as possible to officials in the watershed as to the river levels that may be expected to occur.

The flood forecast system has evolved over the last 40 years spurred on by the construction of Shand Dam in 1942 and the occurrence of major floods in 1948, 1954, 1972, 1974, and 1975. Hydrometric data collection began in earnest in 1947 and expanded to its present degree in 1973. Automatic data collection began in 1960. After the 1974 flood, streamflow forecasting using computer models began and the present flood warning system was developed.

The philosophy used in the development of the flood forecast system since 1974 has been to start with a simple working system and improve as time, money, and the state-of-the-art allow. The current flood forecast system has been working since 1976 and is being expanded and improved each year.

3.0 DATA COLLECTION

No river control system can operate without an efficient system for monitoring critical parameters to show quickly current conditions throughout the basin. The Grand River Conservation Authority monitors streamflow, meteorological conditions and operational conditions at the dams. We work very closely with agencies such as Atmospheric Environment Service and Inland Waters Directorate of Environment Canada; and the Conservation Authorities & Water Management Branch of the Ministry of Natural Resources.

3.1 Hydrometric Data Collection

The Authority operates a system of 30 water level gauges. The locations of these stations are shown in Figure 2. Of these, 16 are operated by the Authority alone, with the remainder being joint operations with Environment Canada. In addition to this, Environment Canada has several other gauges throughout the watershed.

Each gauge station is equipped with a Bristol Metameter transmitter which transmits water levels every 15 seconds over dedicated telephone lines to a chart recorder. Fourteen of the receivers, from gauges measuring reservoir inflow and discharge, are located at respective dams: two at Luther Dam, three at Shand Dam, four at Conestogo Dam, two at Guelph Dam, two at Woolwich Dam, and one at Laurel Creek Dam. The remaining sixteen receivers are located in the Flood Control Centre in Cambridge.

The signal transmitted is a pulse-duration signal representing a percentage of the full range of the gauge. As such, it is only accurate to one percent of the range of the gauge and will not meet Environment Canada's standards for historical data archival. However, it is accurate enough for real-time forecasting of high flows. The four gauges used for planning low flow augmentation releases from the reservoirs are equipped with a second transmitter which operates for low stages and transmits signals representing the level as a percent of the lower ten percent of the range of the gauge. Accuracy is improved for low flows in this manner.

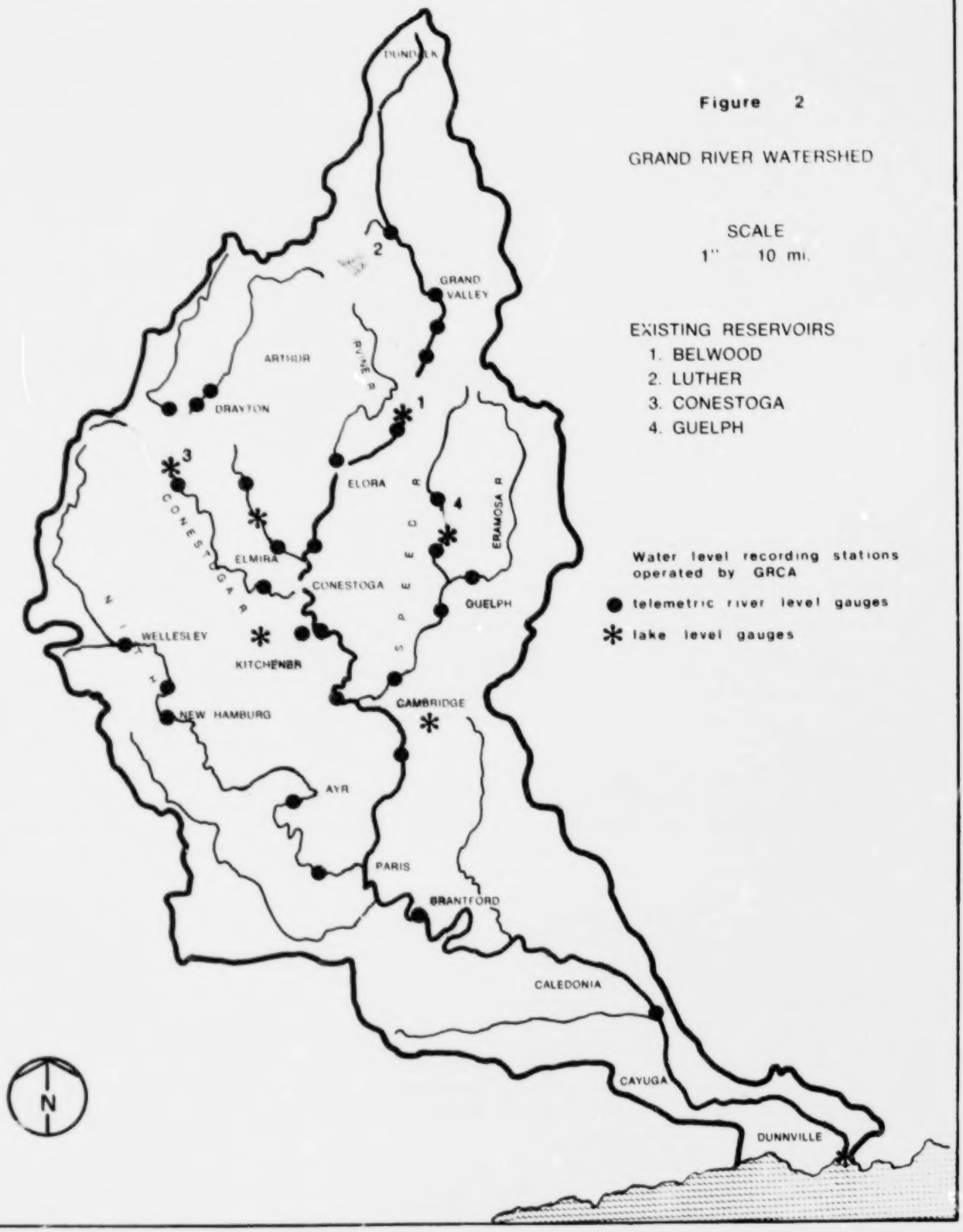


Figure 2

GRAND RIVER WATERSHED

SCALE
1" 10 mi.

EXISTING RESERVOIRS
1. BELWOOD
2. LUTHER
3. CONESTOGA
4. GUELPH

Water level recording stations operated by GRCA

- telemetric river level gauges
- lake level gauges

Streamflow is obtained by reading the water level from the chart and extracting the corresponding flow from gauge rating tables. The water level readings and corresponding flows from receivers located at the dams are reported by radio to the Flood Control Centre daily or on request. The gauges at the main dams serve two roles. They are part of the total monitoring system, and they provide operational data to the operators in the case that they are cut off from the Flood Control Centre.

In the event that the telephone lines are out, the streamflow measurements required to make a streamflow forecast are sent by radio from the gauge station by river watch personnel.

Leopold-Stevens A-35, E-type, or F-type water level recorder are also located at each gauge station, from which water levels for historical record are extracted.

Lake levels are also recorded at six reservoirs and at Lake Erie. Lake levels are read from the charts by Authority staff and are reported by radio to the Control Centre.

Automatic data collection by the computer from the Bristol receivers in the Control Centre and the major reservoirs is planned for 1984 and 1985. This will eliminate the need to manually extract the data from the charts for real-time forecasting.

3.2 Meteorological Data Collection

3.2.1 Precipitation

Precipitation is the most important weather parameter monitored. Each authority installation is equipped with a standard rain gauge which is checked daily. The gauge reader has standing instructions to report to the Control Centre or to the Duty Officer if there is 25mm or more rain in 24 hours. Reports are radioed in on a more frequent basis if severe rainfall events are judged capable of producing problems.

The Authority also operates a system of nine tipping-bucket recording rain gauges. These provide continuous record for both flood forecasting and hydrologic analysis. Under normal conditions, the recording charts are returned to the Control Centre at the end of each week. When necessary for flow forecasting, the area operator reports the rainfall distribution to the Control Centre by radio.

The locations of the precipitation gauges are shown in Figure 3.

Radar facsimiles showing the location and relative intensity of rainfall in Southwestern Ontario are received by the Authority from Environment Canada's Weather Radar Station at Exeter and are used to assess the areal extent of the rainfall.

The existing network of precipitation data does not always represent the precipitation over the basin adequately enough for accurate runoff forecasting, especially during convective thunderstorms. The availability of additional precipitation data from weather radar should assist in resolving this problem.

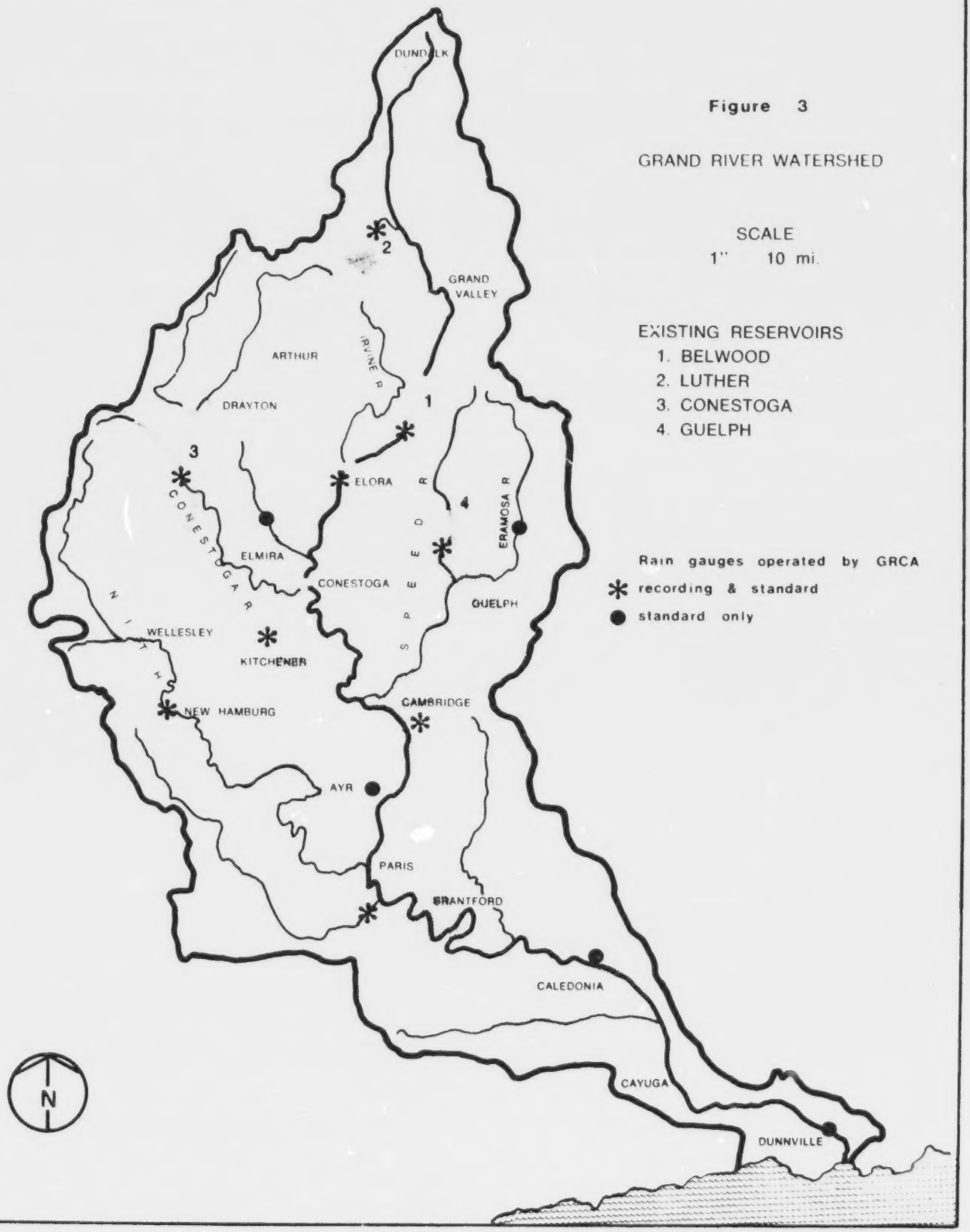


Figure 3

GRAND RIVER WATERSHED

SCALE
1" 10 mi.

EXISTING RESERVOIRS
1. BELWOOD
2. LUTHER
3. CONESTOGA
4. GUELPH

Rain gauges operated by GRCA
* recording & standard
● standard only

3.2.2 Snow Surveys

While rainfall is a critical parameter in river control, the Authority spends as much effort on snowmelt. Snowfall is monitored in the same manner as rainfall. However, a much more critical parameter is snowpack, the source of the meltwater. The authority operates 12 snowcourses at which the depth and water content of the snow are determined on a bi-weekly basis and as necessary to determine the runoff potential in the snowpack. The locations of the snow courses are shown in Figure 4.

3.2.3 Temperature

The third weather parameter monitored is temperature. Daily maximum and minimum temperatures are recorded at all Authority installations. This is mainly used as an indication of the timing of the snowmelt in the spring runoff periods.

4.0 WEATHER FORECASTING

In providing adequate flood protection and warning, concise, accurate weather forecasts are vital. The Authority officially receives weather information from two sources: Environment Canada and the Ontario Ministry of Natural Resources. Environment Canada forecasts are received by telex and include:

1. forecasts twice daily giving general weather outlook and temperature high and low;
2. five-day weather outlook daily;
3. quantitative precipitation forecast daily;
4. advisories and warnings of forecast severe weather conditions, updated as necessary.

Forecasts are received by telex from MNR Streamflow Forecast Centre when predicted weather conditions may cause flooding problems.

The Authority staff do not have meteorological training and rely on the above sources for interpretation of weather forecasts. When more information is required, phone calls are placed to the MNR Streamflow Forecast Centre and occasionally to the Ontario Weather Centre at the Toronto International Airport.

Generally, the effect of the Great Lakes makes weather forecasting for Southwestern Ontario very difficult, and therefore locally inaccurate. For this reason, flood warnings are not issued based on weather forecasts. However, forecasts of severe weather conditions alert staff to potential problems: duty officers for the Flood Control Centre and the dams stay withing easy reach and monitor the weather conditions. On occasion, such as the approach of Hurricane Frederick in 1979, the Control Centre is manned on a 24-hour basis. On other occasions, such as the approach of a wide-spread frontal storm on Friday afternoon with a heavy snowpack on the ground, flood advisories are issued to municipal officials in the watershed.

5.0 PREPARATION OF STREAMFLOW FORECAST REPORTS

The Streamflow forecasts for flood warning purposes are currently made based on the streamflow recorded at all of the gauges upstream of each point of interest.

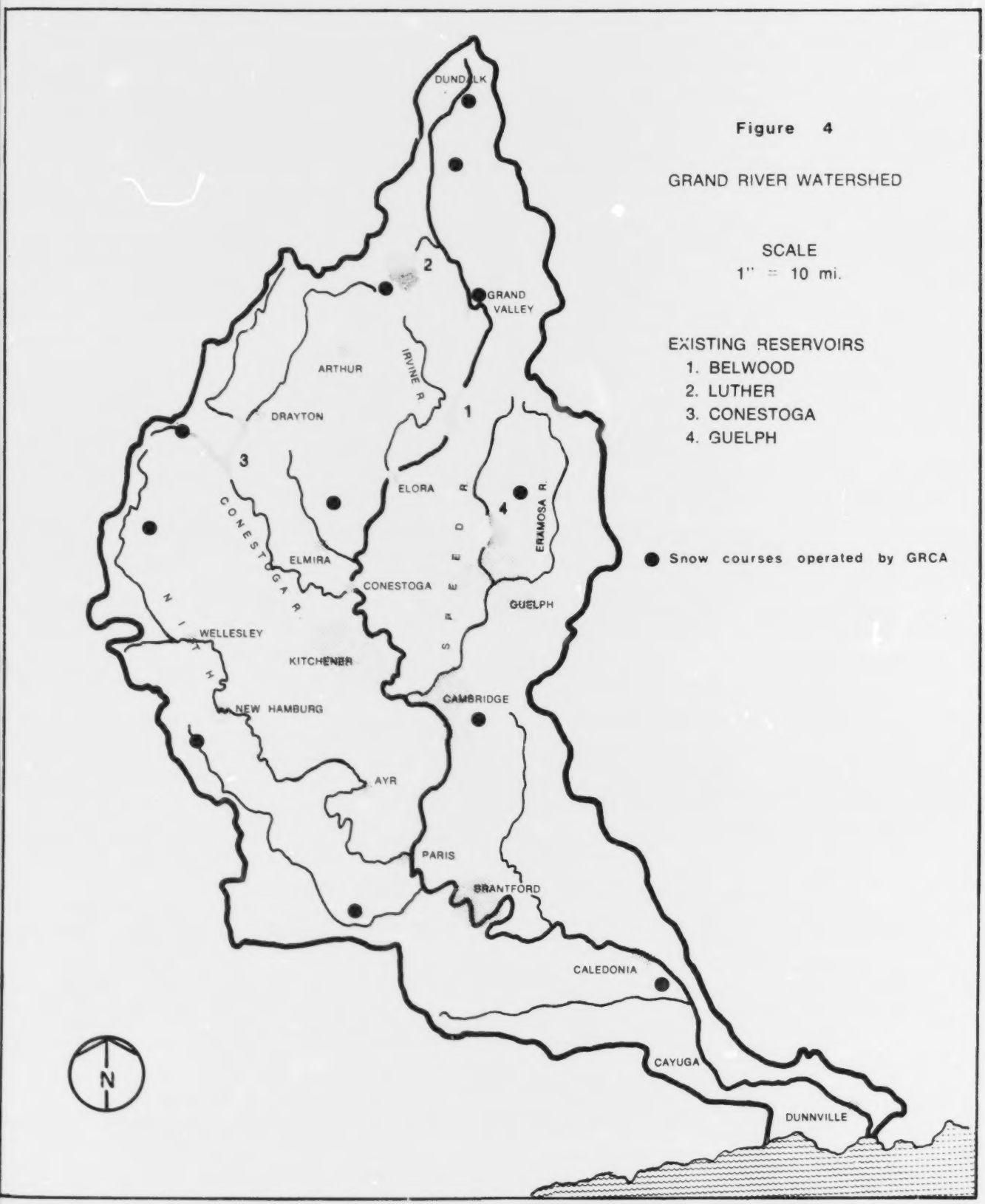


Figure 4

GRAND RIVER WATERSHED

SCALE
1" = 10 mi.

EXISTING RESERVOIRS
1. BELWOOD
2. LUTHER
3. CONESTOGA
4. GUELPH

● Snow courses operated by GRCA

The forecasts are prepared with the use of a DEC VAX11/750 computer. The computer program used to forecast streamflow was developed by Authority staff specifically for the Grand River watershed. A simple version for the central portion of the watershed was first used in the 1977 spring freshet on an IBM 5100 desktop computer. Modifications and expansions are constantly being carried out to improve accuracy and efficiency. The program was converted to run on the VAX11/750 when this minicomputer was obtained in 1982. The philosophy in developing the program has been to always have a working version ready to be implemented on a moment's notice.

Streamflow and reservoir levels are collected from the telemetric gauges and from operator reports and are manually entered into the computer. A sample input form is shown in Figure 5. Input of any time interval (in multiples of one hour) may be used; output has an hourly time interval. The program works with 120 hours of data: 48 - 72 hours of observed data, and 48 - 72 hours of projected data. A summary printout showing the forecast peak flow and the time of its occurence is automatically produced. A sample is shown in Figure 6. Tables of hourly flows can be obtained for any or all stations optionally.

While a maximum of 72 hours of observed data is retained for use by the forecast model, all observed data is archived for future use. At any time during the event, natural flows can be calculated. This is normally done at the end of the event and is used for assessing the effectiveness of reservoir operation.

About 20 minutes is currently required to prepare a forecast: 15 minutes to extract the required data from the telemetric charts and about 5 minutes to enter the data into the computer. The turnaround time once the data has been entered is less than one minute. During the period February to May, forecasts are prepared twice each day when the dam operators reports are received. During a period of high flow, forecasts are prepared as they are required, often every three hours. Forecasts may be prepared every hour, if necessary.

The computer system is connected to the emergency generator at the Administration Centre. In the event of a power failure, the generator provides the necessary power to operate the computer.

5.1 Flow Forecasting

At head water flow points, flow is predicted based on the assumption that it has reached its peak at the time of running and will begin recession.

Within each reach, the following steps are carried out:

a) the flow at the upstream flow point is routed to the downstream flow point to determine what portion of the downsteam flow is due to the flow at the upstream flow point;
b) the routed upstream flow is subtracted from the flow observed at the downstream flow point to determine the local flow;
c) the local flow is projected based on the assumption that it has reached its peak at the time of running and will begin recession;
d) the predicted local flow is added to the routed upstream flow projection to predict the flow at the downstream point.

Page 1

Hour 0800 Date Dec 25, 1982

Station	Current Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow
Legatt	54.1										
Marryille	98.1	16	30.5	24	64.0						

	Current Storage	Hr	Storage	Hr	Storage	Hr	Storage	Hr	Storage	Hr	Storage
[illegible]	16116	12	13945	24	15545						

	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow
Drayton	50.7	16	43.5	24	48.3						

	Current Storage	Hr	Storage	Hr	Storage	Hr	Storage	Hr	Storage	Hr	Storage
Conestogo Dam	17338	12	15823	24	14917						

	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow
[illegible]	13.0	16	4.99	24	8.10						

	Current Storage	Hr	Storage	Hr	Storage	Hr	Storage	Hr	Storage	Hr	Storage
Guelph Dam	2231	12	1845	24	1972						

Figure 5 Forecast Model Input

PROJECTED RESERVOIR DISCHARGE

Reservoir	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow
Shand Dam										
Conestogo Dam										
Guelph Dam										

Hour 0800 Date Dec 25, 1982

Station	Current Flow	Hr	Flow	Flow	Hr	Flow	Flow	Hr	Flow	Flow
Shand Dam	22.2									

	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow
Salem	40.2	2	23.2	7	32.1						
West Montrose	75.6	5	70.8								

	Flow	Hr	Flow	Flow	Hr	Flow	Flow	Hr	Flow	Flow
Conestogo Dam	16.9									

	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow
St. Jacobs	46.2	15	53.2								
Elmira	11.0										
Doon	150	2	143								

	Flow	Hr	Flow	Flow	Hr	Flow	Flow	Hr	Flow	Flow
Guelph Dam	7.48									

	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow	Hr	Flow
Cramosa	6.23										
Hanlon	16.4	16	11.6	24	14.0						
Beaverdale	18.4										
Galt	171	3	154								
Nithburg	74.5	19	74.5								
New Hamburg	74.9	24	70.2								
Ayr	60.9	24	20.3								
Canning	24.7	24	16.0								
Brantford	190										
York	161										

GRAND RIVER CONSERVATION AUTHORITY

FORECAST SUMMARY
PREPARED DEC 25, 1982, AT 800 HRS

RESERVOIRS	PRESENT INFLOW (M3/S)	PRESENT DISCHARGE (M3/S)	PRESENT STORAGE (1000M3)	FORECAST PEAK INFLOW (M3/S)	FORECAST MAXIMUM STORAGE (1000M3)	VOLUME INFLOW TO DATE (MM)
SHAND DAM	22.5 (F)	22.2 (R)	16116. (R)	116.6 AT 2300 DEC 24, 1982*	23083. AT 300 DEC 27, 1982	6.
CONESTOGO DAM	101.3 (R)	16.9 (R)	17338. (R)	108.1 AT 2300 DEC 24, 1982*	21740. AT 1500 DEC 26, 1982	12.
GUELPH DAM	18.8 (R)	7.5 (R)	2231. (R)	20.2 AT 1300 DEC 25, 1982	2877. AT 800 DEC 26, 1982	5.

GAUGE STATIONS	PRESENT FLOW (M3/S)	PRESENT STAGE (M)	FORECAST PEAK FLOW (M3/S)	FORECAST PEAK STAGE (M)	FORECAST FLOODING AT: MINOR	MAJOR
LEGATT	54.1 (R)		54.1 AT 800 DEC 25,1982*			
MARSVILLE	98.1 (R)		103.5 AT 1400 DEC 25,1982			
DRAYTON	50.7 (R)		50.7 AT 800 DEC 25,1982*			
ARMSTRONG MILLS	13.0 (R)		13.0 AT 800 DEC 25,1982*			
SALEM	40.2 (R)		40.2 AT 800 DEC 25,1982*			
WEST MONTROSE	75.6 (R)		78.1 AT 1600 DEC 25,1982			
ST JACOBS	46.2 (F)		53.2 AT 1800 DEC 24,1982*			
ELMIRA	11.0 (R)		11.0 AT 800 DEC 25,1982*			
DOON	150.0 (R)		151.6 AT 1000 DEC 25,1982			
BRAMOSA	6.2 (R)		6.2 AT 800 DEC 25,1982*			
HARLOW	16.4 (R)		16.8 AT 1300 DEC 25,1982			
BEAVERDALE	18.4 (R)		19.5 AT 1600 DEC 25,1982			
GALT	171.0 (R)		177.7 AT 1400 DEC 25,1982			
NITHBURG	24.5 (S)		24.5 AT 1900 DEC 24,1982*			
NEW HAMBURG	94.9 (R)		94.9 AT 800 DEC 25,1982*			
AYR	60.9 (R)		97.5 AT 2300 DEC 25,1982			
CANNING	24.7 (R)		86.0 AT 700 DEC 26,1982			
BRANTFORD	190.0 (R)		235.4 AT 2100 DEC 25,1982			
YORK	161.0 (R)		232.2 AT 700 DEC 26,1982			

(R) RISING
(S) STEADY
(F) FALLING
* PEAK HAS OCCURRED

Figure 6 Forecast Model Output

5.2 Channel Routing

The Muskingum method of channel routing is used. Reaches are defined by the location of streamflow gauges. Coefficients have been developed for each reach by trial and error. Observed hydrographs at an upstream gauge for a number of flood events were routed with a variety of coefficients to a downstream gauge. Coefficients were selected that would best fit the upstream hydrographs under the downstream hydrographs. In this way it was not necessary to estimate the local flow entering the stream between the gauges. Muskingum routing performs reasonably well for the average to maximum observed spring freshet in the upper and middle watershed.

With the increased computing power now available, techniques are being sought to improve routing. Variable storage coefficient and storage indication routing are being implemented. Depth-travel time-discharge and storage-discharge relationships have been defined using the HEC-2 Water Surface Profile program and input developed during floodplain mapping studies. Verification with observed hydrographs has shown improvement in the routing, particularly in the lower reaches of the Grand and the major tributaries where overbanks are wider and slopes are lower.

5.3 Reservoir Routing

The inflow to each reservoir is calculated based on the discharge from the reservoir and the change in reservoir storage. Storage is predicted based on the projected inflow. While no attempt has been made to program the computer to optimize reservoir operations, the effect of planned reservoir operations on reservoir levels and downstream flows can be tested.

5.4 Accuracy of Streamflow Forecasts

As the flow at each upstream station peaks, the forecast at the downstream station under consideration becomes more accurate. Initially, flows are underestimated and forecasts indicate the minimum that the flows are expected to rise. For the middle portion of the watershed, peak flows can be predicted 6 to 9 hours in advance with errors of 5 percent on stage and 10 percent on flow. For the lower portion of the watershed, peak flows can be predicted 12 to 15 hours in advance with the same accuracies.

5.5 Runoff Forecasting

For rain only events, forecasts of runoff are made using the Antecedent Precipitation Index (API), a technique which relates runoff to a soil moisture index and a seasonal index. When a first estimate of expected runoff has been made using this technique, flow resulting from this runoff is combined with the current river flow to forecast a possible resulting flow at points of interst. Forecasts made in this manner aid in the decision to issue a flood advisory.

For snowmelt or rain on snow events, runoff volumes are estimated by staff based on experience. Streamflow forecasts for a range of possible runoff volumes are made. Attempts to derive coefficients for degree-day snowmelt modelling have not been very successful to date. However, damaging floods are more likely caused by rain on snow events.

6.0 COMMUNICATIONS

6.1 Duty Officer System

The Authority operates a duty officer system to ensure that, at all times, one member of the Flood Control Centre staff is available and alert to potential problems in the watershed.

During flood emergencies, the Control Centre at the Administration office is manned around the clock by one or more of the duty officers. The responsibility of the duty officer is to collect all information on watershed conditions, send out instructions for dam operation and river conditions monitoring, update flood warning and advisory messages, and maintain contact as necessary with municipal officials, as approved by the Flood Coordinator or his alternate.

In addition to the Flood Coordinator, there are six duty officers, three of whom are able to assume the role of Flood Coordinator if necessary.

6.2 River Watch System

The entire watershed is divided into twelve smaller areas which are assigned to various area superintendents (shown in Figure 7). These superintendents are responsible for field contact and reconnaissance during flood periods. Acting on instructions from Central Control, they make inspections, report on conditions, etc. These reports may be required because of ice problems, severe local rains, unsubstantiated reports of local flooding or any other reason. In the case of telephone failure, the River Watch personnel function as a communication link between Central Control and the local municipal officials via the Authority's two way radio network. By acting as a mobile reconnaissance force, the Authority field staff operating in this system perform one of the most important roles during emergency periods.

6.3 Other Staff

During flood emergencies, the entire staff of the Authority may be pressed into duty in one way or another. A secretarial pool is set up to ensure adequate staff is available to answer telephone calls from the general public. Personnel from the Community Relations Division aid in liaison with the news media throughout the watershed and take as many still and movie films as possible to produce documentation of the flood. Staff from the Resource Planning Division are in the field to accurately record peak flood levels for use in administration of the Authority Regulations re Fill, Construction and Alteration to Waterways.

6.4 Radio Network

The Authority operates a radio network of ten base stations and sixty mobile and portable units. Communications between the Control Centre and river watch personnel are carried out via the radio network, ensuring that contact can be maintained continuously from the field and in the event of telephone failure. Most of the base stations operate on an emergency generator in the event of power failure. In any case, mobile units operate independently and can be relied upon in case of power failure.

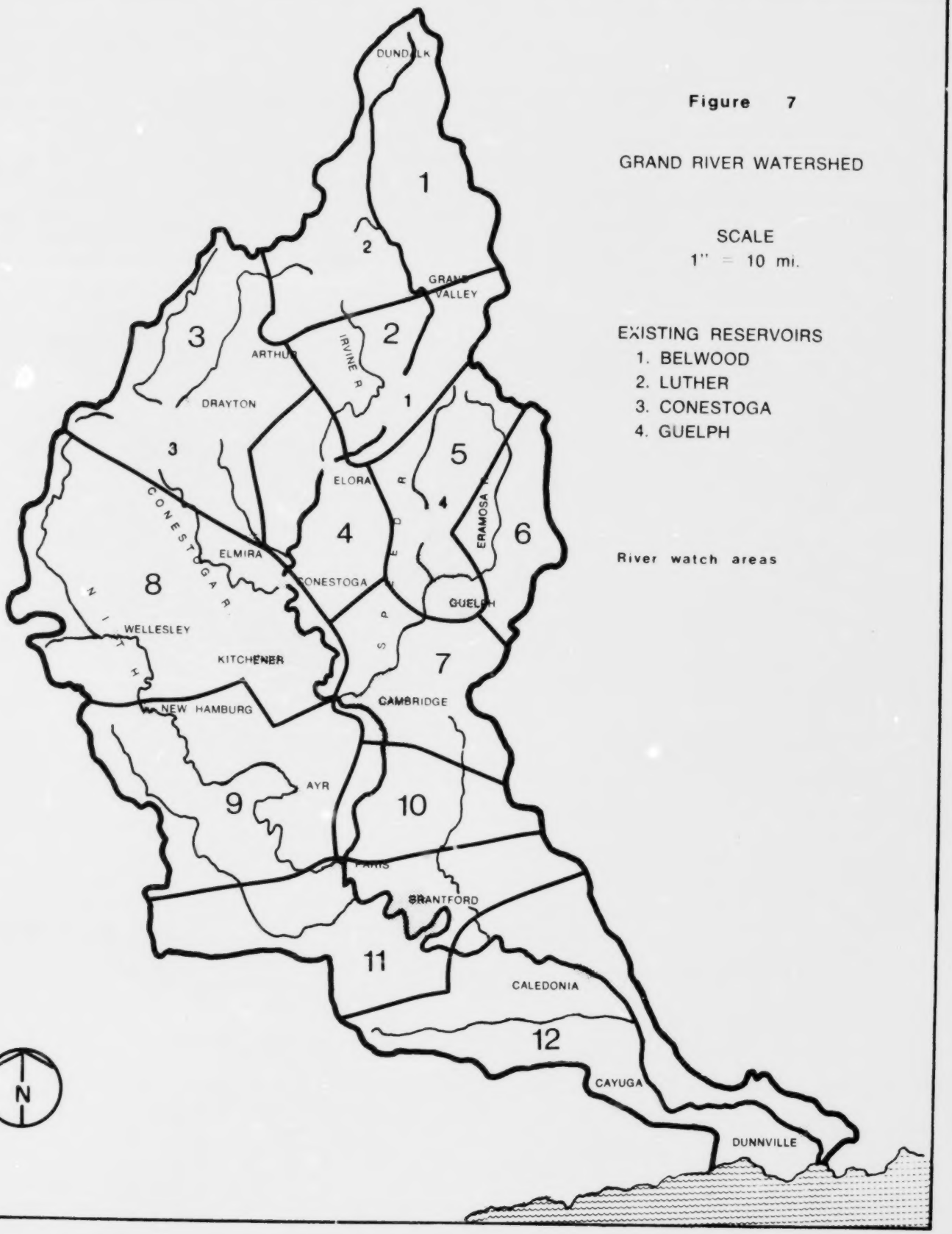


Figure 7

GRAND RIVER WATERSHED

SCALE
1" = 10 mi.

EXISTING RESERVOIRS
1. BELWOOD
2. LUTHER
3. CONESTOGA
4. GUELPH

River watch areas

6.5 Flood Warning System

The aim of this system is to provide routine flood bulletins to certain selected agencies and officials in the watershed and, in times of flood danger, to pass the necessary warning as rapidly as possible to concerned officials and to citizens whose lives and property may be in danger.

As the Grand River Conservation Authority has no jurisdiction as to the method of continuing the fan-out in the municipalities, the municipalities are responsible for producing their own fan-outs.

6.5.1 General Flood Bulletins

A letter from the Ontario Minister of Natural Resources addressed to all municipalities in Ontario is sent annually and consists of a general reminder of the danger inherent during the spring breakup period.

General bulletins describing the conditions posing a flood hazard, and the extent of the danger, are issued by the Grand River Conservation Authority as conditions warrant. These bulletins are mailed to members of the Authority's Executive Committee and Water Management Advisory Board, Ontario Ministry of Natural Resources Conservation Authorities & Water Management Branch, Administrators or Clerks, and Police Departments and other Officials designated by watershed municipalities, and to press, radio and television news department for those facilities with audiences in the watershed. Receipt of these bulletins initiate a check on flood plans in the municipalities.

After the reservoirs are filled from the Spring runoff, flash floods that may occur during the months of April, May and June do not allow a great deal of advance warning; thus no general bulletins are issued.

6.5.2 Emergency Flood Warning

A number of agencies, municipal departments and individuals bear responsibility in varying degree for the efficient operation of the Emergency Flood Warning System. An outline of these responsibilities follows; reference to Figure 8 will be of assistance to the reader.

Grand River Conservation Authority

The GRCA is responsible for operations of the Authority Flood Control Centre during anticipated or actual flood periods. The Flood Control Centre duty officer prepares the necessary Emergency Flood Warning messages.

These messages are passed simultaneously or in the following order to:
1. The Officer in charge of Communications, Water Regional Police Headquarters;
2. Watershed radio and television stations.

The steps in this procedure are shown in Figure 9.

Where possible, emergency flood warning messages contain both arrival and crest times for specific locations, and expected flood stages.

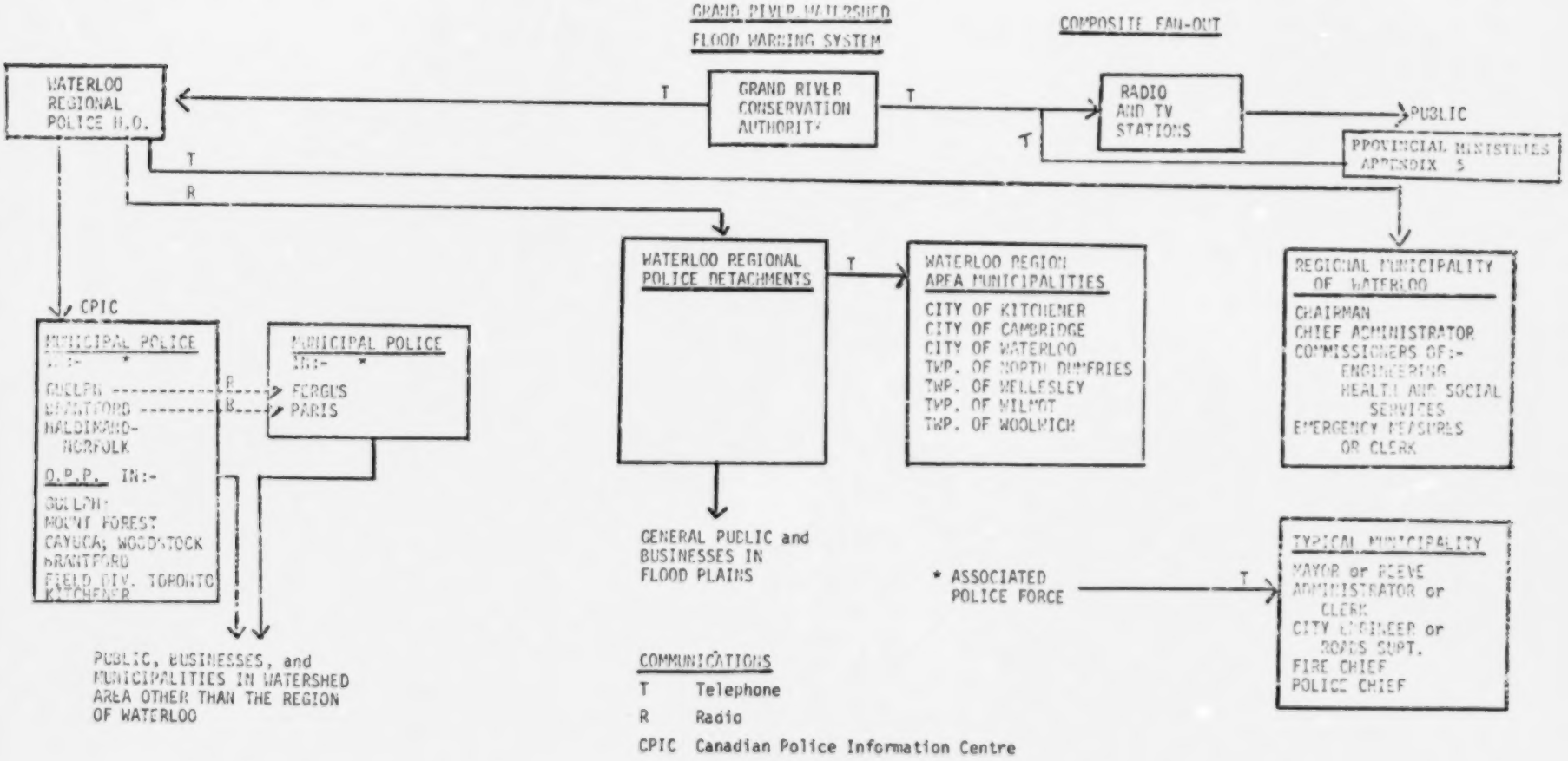

GRAND RIVER WATERSHED
FLOOD WARNING SYSTEM
COMPOSITE FAN-OUT
WATERLOO REGIONAL POLICE H.Q.
T
GRAND RIVER CONSERVATION AUTHORITY
T
RADIO AND TV STATIONS
PUBLIC
T
PROVINCIAL MINISTRIES APPENDIX 5
T
R
CPIC
MUNICIPAL POLICE
IN:- *
GUELPH
BRANTFORD
HALDIMAND-NORFOLK
O.P.P. IN:-
GUELPH
MOUNT FOREST
CAYUGA; WOODSTOCK
BRANTFORD
FIELD DIV. TORONTO
KITCHENER
R
R
MUNICIPAL POLICE
IN:- *
FERGUS
PARIS
WATERLOO REGIONAL POLICE DETACHMENTS
T
WATERLOO REGION AREA MUNICIPALITIES
CITY OF KITCHENER
CITY OF CAMBRIDGE
CITY OF WATERLOO
TWP. OF NORTH DUMFRIES
TWP. OF WELLESLEY
TWP. OF WILMOT
TWP. OF WOOLWICH
REGIONAL MUNICIPALITY OF WATERLOO
CHAIRMAN
CHIEF ADMINISTRATOR
COMMISSIONERS OF:-
ENGINEERING
HEALTH AND SOCIAL SERVICES
EMERGENCY MEASURES OR CLERK
GENERAL PUBLIC and BUSINESSES IN FLOOD PLAINS
* ASSOCIATED POLICE FORCE
T
TYPICAL MUNICIPALITY
MAYOR or REEVE
ADMINISTRATOR or CLERK
CITY ENGINEER or ROADS SUPT.
FIRE CHIEF
POLICE CHIEF
PUBLIC, BUSINESSES, and MUNICIPALITIES IN WATERSHED AREA OTHER THAN THE REGION OF WATERLOO
COMMUNICATIONS
T Telephone
R Radio
CPIC Canadian Police Information Centre

Figure 8

GRAND RIVER CONSERVATION AUTHORITY

FLOOD WARNING MESSAGES - PROCEDURE

Step 1 - Duty Officer — Prepares draft message.

2 - Assistant General Manager, or General Manager, or Chairman — Approves message (If none available proceed to 3).

3 - Duty Officer proceeds

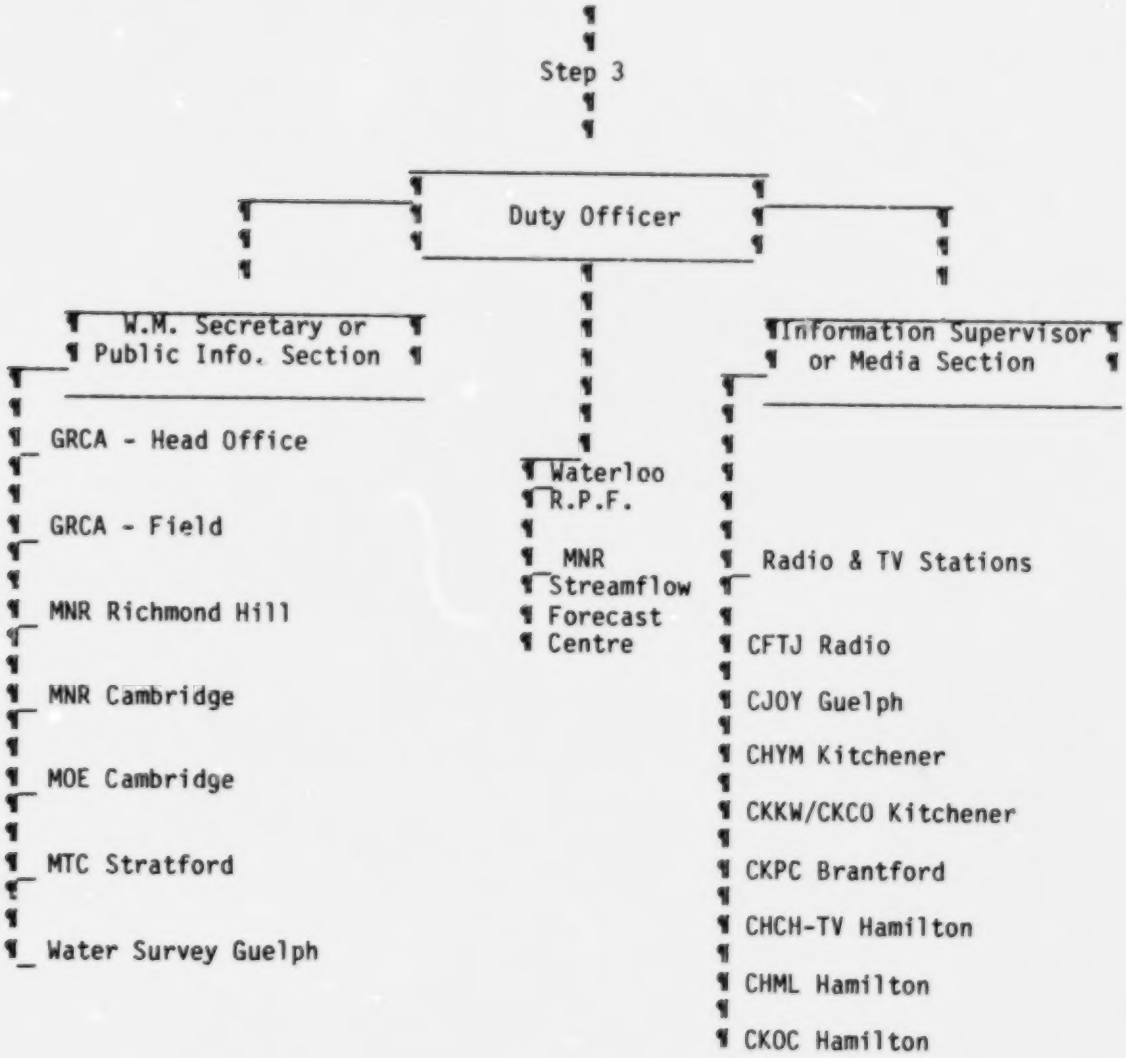


FIGURE 9

All Warning messages are passed to all Watershed Police Detachments to maintain the routine of police communications.

Flood warning messages issued by the GRCA include in the preamble to the message the term "Advisory" or "Action" message for a particular municipality or part of the watershed.

Waterloo Regional Police

Emergency Flood Warnings are received by the Officer in charge of Communications, Waterloo Regional Police Headquarters from the Flood Control Centre, G.R.C.A. These messages are recorded on tape.

A police officer equipped with a portable police radio is sent by Waterloo Regional Police H.W. to the GRCA Flood Control Centre immediately on receipt of the first action message to be a back-up to maintain contact with Police H.Q. in the event of telephone failure.

Warning messages, exactly as received except for routing procedures required by the Canadian Police Information Centre, are sent immediately to all police forces in the watershed and to the Ontario Provincial Police Field Division in Toronto.

On receipt of an "Advisory" message from the GRCA, the Regional Police pass it on to all Waterloo Regional Area municipalities and to all other Watershed Police Departments. The Regional Police do not warn the general public or businesses on receipt of an "Advisory".

On receipt of an "Action" message from the GRCA, the Regional Police pass it to all Regional Area municipalities and other Watershed Police Departments, and warn all households and businesses within the threatened areas, in accordance with the contents of the message.

"Test" messages are issued annually prior to spring breakup and are handled in the same manner as the "Advisory" messages.

Radio and Television Stations

Emergency flood warning messages are passed to all radio and television stations in the watershed from the Flood Control Centre, GRCA.

STREAMFLOW FORECASTING IN MANITOBA

V. M. Austford[1], R. J. Bowering[2] and A. A. Warkentin[3]

ABSTRACT: The paper provides an overview of streamflow forecasting methodologies and flow forecasting activities conducted by the Water Resources Branch, Manitoba Department of Natural Resources. Operation of the forecast centre and communication links to jurisdictions using forecasts as well as the media and the public are also described.

This paper was prepared for the Technical Workshop on Streamflow Forecasting to be held in Toronto (Downsview), November 22 to 24, 1983.

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INTRODUCTION

The major streamflow forecasting activity of the Manitoba Water Resources Branch is directed toward spring runoff forecasting, in particular as it relates to urban and rural flooding and operation of flood control works. The Branch is also involved in the forecasting of river flows during severe droughts when river levels become critically low. Where the outflow from a lake or reservoir is controlled, regularly updated inflow forecasts are prepared to facilitate the efficient operation of the outlet so as to optimize reservoir levels and downstream flows.

Streamflow forecasting is conducted at the head office in the City of Winnipeg. Regional offices provide input data and are provided with forecasts from the head office by either telephone or telecopier. Regular contact is maintained with personnel from the Canada Water Resources Branch and the Atmospheric Environment Service for the latest hydrometric data at federal monitoring sites and for updates on weather forecasts. The streamflow forecasting function is conducted by the Hydrology Section as part of a broader program of hydrologic services provided for the Water Resources Branch. At present the Flood Forecasting Centre has a full time staff of two as well as a staff of three engaged under a shared-cost program with Canada which will be described later. During the active spring runoff period the entire Hydrology Section assists in flow monitoring and forecasting, through the acquisition and organization of hydrometeorological data. During major floods, additional assistance is obtained from other sections of the Water Resources Branch and from the Engineering and Construction Branch also of the Manitoba Department of Natural Resources.

SPRING RUNOFF FORECASTS

The disastrous flood of 1950 on the Red River caused extensive damages which at Winnipeg alone totalled in excess of $100,000,000. The 1950 Flood provided the impetus toward the implementation of streamflow forecasting in Manitoba. In 1953 the "Report on Investigations into Measures for the Reduction of the Flood Hazard in the Greater Winnipeg Area" prepared by the Department of Resources and Development, Government of Canada suggested that a flood forecasting system be established to facilitate not only the efficient operation of any flood control works which may be provided in the future, but also to supply as much advance flood warning to the public as may be possible. In 1954, the Premier of Manitoba, in cooperation with the Federal Minister of Northern Affairs and National Resources, the Federal Minister of Transport and the Mayor of Winnipeg in his capacity as Chairman of the Administrative Board of the Greater Winnipeg Sanitary District established a Flood Forecasting Committee to scrutinize and approve forecast information on the Red and Assiniboine Rivers prepared by the Water Resources Branch of the Manitoba Department of Mines and Natural Resources. The Committee has functioned since that time and is now chaired by the Director of the Manitoba Water Resources Branch and has representation from the Canada Water Resources Branch, the Atmospheric Environment Service and the Waterworks and Waste Disposal Division, City of Winnipeg.

The Manitoba Water Resources Branch prepares two types of spring runoff forecasts: preliminary and operational. Preliminary forecasts, or flood outlooks, are prepared before the melt period to give an indication of what levels or range of levels may be expected. Operational forecasts

are made once snowmelt has begun and predict daily as well as peak river levels.

Preliminary Forecasts

Spring runoff outlooks give an indication of the peak water level to be expected under various probabilities of future weather conditions. Since outlooks are issued prior to the start of runoff, the date of the peak cannot be predicted.

A statistical antecedent precipitation index (API) type model, known as MANAPI is used. The API is computed by adding weighted monthly precipitation from May to October and by expressing the total as a percent of normal. The monthly weighting factors used are as follows:

May	June	July	August	September	October
.07	.08	.12	.18	.25	.30

The procedure of forecasting tributary runoff is based on a multiple regression analysis of historical data. The dependent variables are runoff depth and peak flow. The independent variables are winter plus spring precipitation, API, melt index and sometimes the winter temperature index or the previous spring runoff. The resultant equation is a product/power type function. The regression analysis is done by using an optimization technique on the power function rather than by undertaking a least squares regression of the transformed equation. An advantage of this technique is that equal weight is given to all data values whereas in the more common logarithmic form much more weight is given to the lower values. Also the variance is computed and assessed in the original units rather than in the transformed logarithmic units. The following forecasting

equations for the Boyne River near Stephenfield provide an example of the MANAPI model:

$$\text{Peak (cfs)} = 0.2093\ (P)^{2.259} \times (API)^{0.730} \times (MI)^{0.613}$$

$$R = 0.955 \qquad s = 388 \text{ cfs}$$

$$\text{Runoff (inches)} = 2.005 \times 10^{-4}\ (P)^{2.241} \times (API)^{0.866} \times (MI)^{0.241}$$

$$R = 0.933 \qquad s = 0.374 \text{ inches}$$

Preparation of the pre-melt flow forecasts require hydrometric and climatological input data. The Manitoba Water Resources Branch obtains monthly precipitation data for all climatological stations operated by the Atmospheric Environment Service in the Central Region. The Branch obtains similar data from the U.S. National Weather Service for pertinent areas of North Dakota and Minnesota. Monthly precipitation data are obtained from these agencies by teletype with a follow-up copy in the mail. Some precipitation data obtained by the Manitoba Forestry Service and the Water Resources Branch are also used.

Isohyetal analyses of monthly precipitation are prepared based on reported point precipitation values. Precipitation data for May to October are used to compute an API for each station using the weighting factors previously described. The API values for each station are plotted on a large watershed map and an isohyetal analysis is performed. Values of API for specific tributary basins are obtained from the isohyetal analysis.

Station totals of cumulative winter precipitation from November 1 to the forecast date are plotted on a watershed map and an isohyetal analysis is drawn. Values of winter precipitation for specific tributary basins are obtained from the analysis to prepare spring runoff outlooks.

Meteorological forecasts are not used in preparing pre-melt runoff outlooks due to the unreliability of long range weather forecasts. Instead, outlooks are usually based on the lower decile, median and upper decile weather conditions derived from statistical analysis.

On the Red River, a more complex probabilistic procedure has been developed to determine inputs for runoff outlooks. This is based on joint probabilities of meteorological inputs and uncertainties in recorded data, runoff forecast equations and rating curves.

The Water Resources Branch conducts snow surveys in mid-February and mid-March of each year. Isohyetal analyses of these data are performed on a large watershed map. Snow course data are not utilized directly in these flow forecasting procedures, but are sometimes used to adjust cumulative precipitation input at times when sublimation losses from the snowpack have been insignificant.

Operational Forecasts

Operational runoff forecasts, i.e. those forecasts issued after runoff has commenced, are based on a daily time period. The time horizon of the forecast period varies from days to weeks depending on the basin size and on the nature and progression of the runoff event. The horizon is always placed far enough into the future so that the peak flow is included in the period.

For operational forecasting, daily temperature and precipitation data are required. These are obtained from the Atmospheric Environment Service by teletype with a follow-up by mail. The major problem is the lack of an adequate density of real-time precipitation reporting stations. It is very difficult to make accurate estimates of basin precipitation

because of the sparse network, particularly in cases where the precipitation results from atmospheric instability. The Branch also obtains hourly weather and synoptic precipitation via teletype in order to obtain a better indication of the weather elements which affect snowmelt and of the time distribution and areal extent of precipitation.

When runoff on the tributaries is well advanced, the most important input data for flow forecasting are river stages and flows. Accurate observed tributary and main stem flows are required for flood routing and for model updating (tracking). On most tributaries the Branch obtains daily or twice daily river stages by contacting a gauge reader at Canada Water Resources Branch stations. On most main stem and on some tributary hydrometric stations data are obtained by telemark, data acquisition and telemetry systems (DATS), or data collection platform (DCP) units. Discharge measurements are of vital importance during a flood particularly where rating tables are unreliable due to backwater effects, looping, etc. The Canada Water Resources Branch in Winnipeg prepares a computer file of discharge measurements during the spring runoff period. The file is updated daily with the latest real-time data. Manitoba Water Resources Branch staff access this file using an on-line system.

When the spring runoff is relatively high, Manitoba uses as many as six of its own hydrometric crews to obtain additional streamflow measurements. These crews are provided by the Engineering and Construction Branch of the Manitoba Department of Natural Resources. The Engineering and Construction Branch also provides useful additional information on field conditions gathered in the course of its provision of flood fighting services to rural municipalities in Manitoba.

During the snowmelt period, weather satellite imagery is sometimes obtained from the Atmospheric Environment Service in order to monitor the retreat of the snowcover.

Ice jams are not considered in flow routing but peak stage forecasts are accompanied by a warning that higher stages may occur in the event of ice jams.

Operational runoff forecasts are updated by adjusting the predicted tributary runoff volumes based on a comparison of observed and simulated flows up to the forecast date and based on field conditions and data from index areas. Index areas are small drainage basins generally ranging in size from 75 km^2 to 200 km^2, where the Branch conducts detailed snow surveys and where runoff is monitored very closely during the spring break-up by Water Survey of Canada supplemented by measurements by Department of Natural Resources staff. Since index areas are small they exhibit an early indication of the magnitude of the spring runoff over the entire river basin. Once the peak has occurred in the index area it is possible to make a reasonable estimate of the total direct runoff and, hence, of the runoff coefficient from the area. This information is used to adjust the forecasted runoff on nearby major tributaries. This is done with caution, giving due consideration to possible differences in soil moisture, snowpack and spring rain between the index areas and the nearby tributaries. Model updating or "tracking" is achieved by adjusting runoff depths from ungauged tributaries and sometimes by indexing ungauged runoff for a given area to a different gauged tributary.

Model tracking also includes the adjustment of "recorded" flows from the beginning of spring runoff up to the forecast date. Since these data are necessarily provisional and often not confirmed by flow measure-

ments, they are occasionally incorrect. Suspect flows are reviewed and sometimes amended to achieve better tracking. Model updating sometimes involves changing channel routing parameters where these have not been firmly established.

The time period for updating computer runs is the same as for other operational runs. It extends at least to the peak at the downstream point of interest on the main stem. For the Red, Assiniboine and Souris Rivers the run period is normally two to three weeks.

Meteorological forecasts of precipitation and temperature are obtained from the Atmospheric Environment Service. Operational streamflow forecasts are extended beyond the meteorological forecast period by assuming that normal weather patterns will occur.

Unit hydrographs are used to convert forecasted runoff depths to daily discharge hydrographs on tributaries. A computer program makes it easy to superimpose and add tributary hydrographs from snowmelt events and any number of rainstorm events. Only the runoff depth and start date for each event are input. The total tributary flow hydrographs are input internally to a flood routing procedure.

The Muskingum method of channel routing is usually used. This method of routing makes no allowance for changing backwater effects. It is not dynamic and would more appropriately be classified as a kinematic routing procedure. The Manitoba Water Resources Branch has used this model with relative success in flow routing on the Red, Assiniboine and Souris Rivers in Manitoba. Successful calibration of the model is dependent on adequate streamflow records, since the model parameters are not explicitly related to stream channel characteristics. A significant disadvantage of the model is that major errors may result if the model is

used beyond the range of the data used in its calibration. The Modified-Puls routing procedure which relates explicitly to a river channel through an input stage-storage curve has also been used. The difficulty with this model is in acquiring sufficient field data to accurately define the stage-storage curve for each reach of the river channel.

Model performance is evaluated both qualitatively and quantitatively. Qualitative evaluation consists of visually comparing plots of recorded and simulated flow hydrographs. The simulated flow hydrographs used for evaluation are generally those derived with known input data. Forecast hydrographs based on real-time input data are used to qualitatively evaluate the usefulness of real-time flow forecasts.

Quantitative evaluation of model performance is based mainly on correlation coefficients and standard errors of estimate between recorded and simulated runoff volumes and peak flows. Runoff volumes are the main criterion used to evaluate tributary forecasting procedures while peak flows are the main criterion for main stem forecasts.

OFFICE PROCEDURE AND COMMUNICATION LINKS

Preliminary forecasts are prepared by the Water Resources Branch in the third week of February and March of each year and usually at the end of the first week in April if runoff has not yet commenced. Forecasts on the Red and Assiniboine Rivers are reviewed and approved by the Flood Forecasting Committee. A "News Release" with the detailed outlook attached is submitted to the Minister of Natural Resources. If the Legislative Assembly is in session, he tables the "News Release" in the House. If

not, it is immediately released to the media. An example of a "News Release" is shown in Annex A. Following release, the outlook is immediately sent to the Manitoba Emergency Measures Organization and to Emergency Planning Canada. A copy is mailed to all cities, towns, villages and rural municipalities, local government districts and Indian bands in Manitoba as well as to several federal and provincial government officials.

During a spring flood, reports and forecasts are issued daily. The morning is usually devoted to acquisition of data and the preparation of status reports known as "Flood Sheets". An example is shown in Annex B. These information sheets containing that morning's river stages and flows are distributed to flood fighters, various government agencies and the media before noon. Forecasts are also shown on the "Flood Sheets". These are based on forecasts prepared in the late afternoon of the previous day although they may be modified somewhat based on the latest hydrometric information. Major forecast changes and periodic updates are announced by the Minister of Natural Resources through a "News Release" which is distributed as described in the previous paragraph. Minor forecast changes are indicated on the "Flood Sheets". An example of a "News Release" of this type is shown in Annex C.

Communications with respect to runoff monitoring and flow forecasting is done mainly by telephone, telecopier and through the mail. The telephone, teletype and the computer are used to obtain data required for forecast preparation.

OTHER STREAMFLOW FORECASTS

Lake and reservoir inflow forecasts are prepared monthly and after significant rainstorms under normal conditions and may be prepared daily under extreme conditions. Low flow forecasts are prepared on a weekly or monthly basis, depending on the severity of the drought.

STREAMFLOW FORECAST IMPROVEMENT

The Manitoba Water Resources Branch is studying conceptual models under the auspices of the Canada-Manitoba Agreement Respecting Flood Forecasting of the Canada-Manitoba Flood Damage Reduction Program. Three models are being tested in conjunction with a Pilot Project on the Boyne River which is a tributary of the Red River in southern Manitoba. The models include the complex Hydrological Simulation Program-Fortran (HSPF) which is a Stanford based model developed by Hydrocomp for the U.S. Environmental Protection Agency, the well known Streamflow Simulation and Reservoir Regulation (SSARR) Model developed by the U.S. Corps of Engineers and the relatively simplistic Single Linear Unit Reservoir Parametric (SLURP) Model conceived by Environment Canada. These models are being evaluated together with the currently used MANAPI model with respect to their performance, cost of calibration, sensitivity to input data, transferability, cost of maintenance and suitability for real-time flow forecasting. Model evaluation should be complete early in 1984. Improved streamflow forecasting procedures will be applied to selected

sub-basins on the Red, Assiniboine and Souris Rivers if the evaluation indicates that it would be warranted.

An investigation of channel routing procedures is also being undertaken under the Canada-Manitoba Agreement Respecting Flood Forecasting. The One-Dimensional dynamic routing procedure used by the Water Planning and Management Branch, Environment Canada, the SSARR linear reservoir routing and various kinematic routing procedures are being tested on the Boyne River. While these studies are still incomplete, it appears that dynamic routing is unnecessarily complex and too difficult to apply to tributaries which have a relatively steep slope. Dynamic routing will be attempted on main stem channels such as the Red River where, because of the relatively shallow slopes and the significant backwater effects, this type of routing may prove to be feasible and advantageous.

Under the Canada-Manitoba Agreement Respecting Flood Forecasting electronic real-time data acquisition systems are being evaluated. These include telemarks, DCPs and DATS. These systems are connected with water level and rainfall sensing equipment. The period of evaluation to date is insufficient to make judgements in this regard.

ANNEX A

"NEWS RELEASE"

SPRING RUNOFF OUTLOOK FOR MANITOBA

The Water Resources Branch of the Department of Natural Resources has prepared the following spring runoff outlook for Manitoba. The Flood Forecasting Committee met on Wednesday, March 23, 1983 and has reviewed and concurs with the runoff outlooks for the Red and Assiniboine Rivers.

On the Red and Souris Rivers, spring runoff is well underway due to the mild weather and the rainstorm in early March. However, the runoff has slowed down because of the recent cool weather. Runoff has not fully begun on the Assiniboine River.

The Committee advises that there is very little snowcover remaining in the Red River Watershed. With normal weather conditions there will be no overbank flows on the Red River this spring. However, there is a 20 percent chance of spring flooding on the Red River with above normal spring precipitation because the soil moisture is extremely high, ground depressions are generally filled and the soil is still frozen.

On the Assiniboine River, heavy snow and freezing rain during early March have increased the runoff potential significantly from that existing in February. With normal spring weather conditions, overbank flows are likely to occur in the Virden and Griswold areas but not elsewhere. There is a 10 percent chance of a flood as large as that of 1979 on the Assiniboine River. Soil moisture is generally above average in the Assiniboine River Watershed. Snowcover is above average from the

Shellmouth Dam to Wawanesa and normal to below normal elsewhere in the Watershed.

The Manitoba Water Resources Branch advises that on the Souris River, agricultural flooding has been occurring for the past week or so on low-lying farmland adjacent to the River from the International Boundary to Hartney. This has resulted primarily from early rainstorm and snowmelt runoff in North Dakota. While there is little snow remaining in the North Dakota portion of the Souris River Watershed, snowcover in the Saskatchewan and Manitoba Portions of the Watershed is normal to above normal. Soil moisture is very high, particularly in North Dakota and Manitoba. With normal weather conditions, shallow overbank flows will continue throughout most of April from the International Boundary to Hartney. There is a 10 percent chance of a flood as great as that of 1979 on the Souris River this spring.

The Manitoba Water Resources Branch reports that spring flooding is not expected on most smaller watersheds in southern Manitoba unless precipitation from now through the spring runoff period is above normal or if a very rapid snowmelt occurs. Streams which have a relatively high spring runoff potential this year and where there is at least a 20 percent chance of overbank flows with unfavourable weather conditions include the following: Icelandic River, Fisher River, Valley River, Turtle River, most tributaries of the Souris River and most tributaries of the Assiniboine River upstream of Brandon. The soil moisture is generally above normal in these watersheds while snowcover ranges from average to above average.

The Manitoba Water Resources Branch cautions that tributaries of the Nelson River and the Hayes River in far northeastern Manitoba

will experience well above average spring flows due to above normal soil moisture and above normal snowcover.

Further details on spring runoff prospects for specific river basins are appended to this release.

The Manitoba Water Resources Branch states that the flood potential will be monitored closely from now throughout the spring runoff period. Amended forecasts and further news releases will be issued if conditions change significantly.

The following information was available for the preparation of the spring runoff outlook:

1. A snow survey conducted by the Manitoba Water Resources Branch during the period from March 14 to 17, 1983 in southern Manitoba and eastern Saskatchewan.
2. A soil moisture survey conducted by the Manitoba Water Resources Branch at freeze-up in the fall of 1982.
3. Climatological data on summer, fall and winter precipitation in Manitoba and Saskatchewan, obtained from the Atmospheric Environment Service, Environment Canada.
4. Records of fall and winter streamflows in Manitoba and Saskatchewan, obtained by the Water Survey of Canada.
5. Information from various cooperating agencies in the United States, particularly the National Weather Service, concerning conditions in the Red River and the Souris River Basins in North Dakota and Minnesota.

March 23, 1983

APPENDIX - MARCH 22, 1983 SPRING FLOOD PROSPECTS

FORECAST SPRING PEAK STAGES IN METRES

	*Lower Decile	**Median	***Upper Decile	Flood Stage	Dyke Capacity	Recent Peak Stages 1978	1979	1982
RED RIVER								
Emerson	235.0	237.4	240.1	238.72	241.71	239.83	241.18	237.79
Letellier	234.4	236.2	238.7	237.78	240.19	238.44	239.41	236.55
St. Jean	232.6	234.4	237.4	235.19	239.27	236.79	238.47	234.69
Morris	231.3	233.1	236.8	234.52	238.77	235.49	238.13	233.21
St. Agathe	230.3	231.9	234.7	235.25	Not Dyked	233.55	235.64	231.10
St. Adolphe	228.4	230.4	233.2	230.89	235.00	232.05	234.18	229.33
Floodway Inlet	227.7	229.8	232.3	231.65	Not Dyked	231.25	233.32	229.01
Winnipeg (James Ave.)								
Natural	226.2	227.9	230.0	227.25	229.84	230.97	228.17	227.25
Controlled	226.2	226.8	227.0	227.25	229.84	227.62	227.40	226.70
ASSINIBOINE RIVER								
Flood Control Works in Operation						1976	1980	1982
Russell	408.3	408.5	409.3	409.20		409.20	408.32	408
St. Lazare	389.7	390.7	391.7	391.10		392.31	389.85	388.89
Miniota	376.5	377.5	378.7	378.00		379.53	375.14	375.71
Virden	369.2	370.5	370.9	369.90		371.49	367.22	368.22
Griswold	364.2	365.3	365.7	364.50		366.32	362.61	363.39
Brandon (1st St.)	356.9	357.5	358.3	358.90		359.51	355.64	356.43
Portage la Prairie	258.7	259.6	260.3	260.30		260.44	256.93	257.61
Headingley	233.4	233.5	233.5	235.50		234.83	229.86	232.90
SOURIS RIVER						1976	1979	1982
Melita	428.6	429.1	429.3	427.20		430.30	429.42	428.36
Napinka 4NE	426.5	426.9	427.3	425.00		428.55	N/A	426.04
Hartney	421.6	421.9	422.4	420.30		425.06	422.25	420.89
Souris	412.1	412.1	412.5	411.80		415.84	412.14	411.51
Wawanesa	350.3	350.5	351.2	352.80		354.54	350.63	350.04

* The lower decile condition refers to a combination of future weather conditions and other variables, whose severity will be exceeded 90 percent of the time.

** Same as above, except will be exceeded 50 percent of the time.

*** Same as above, except will be exceeded 10 percent of the time.

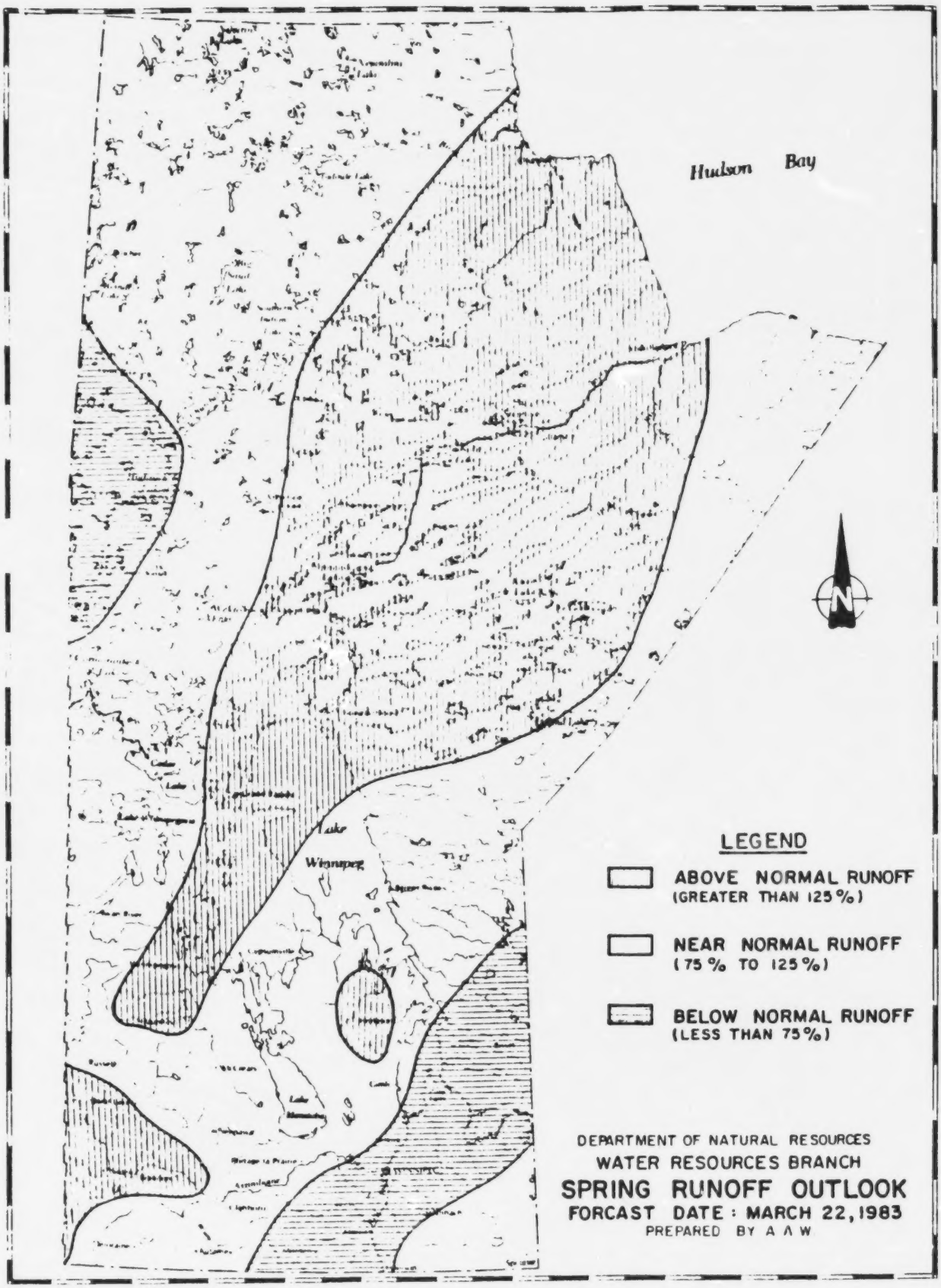
NOTE: 1 metre = 3.2808 feet.
Forecast stages include estimated backwater due to river ice.

SPRING FLOOD OUTLOOKS FOR SMALLER RIVER BASINS

MARCH 22, 1983

	Snowcover	Soil Moisture	Prospects with Normal Weather Conditions
RED RIVER TRIBUTARIES			
Roseau River	Below Normal	Above Normal	No Flooding
All Other Tributaries	Much Below Normal	Above Normal	No Flooding
ASSINIBOINE RIVER TRIBUTARIES			
Tributaries Upstream of Confluence with Souris River	Above Normal	Above Normal	Minor Flooding Possible
Tributaries Downstream of Confluence with Souris River	Near Normal	Above Normal	No Flooding
SOURIS RIVER TRIBUTARIES			
Antler River	Above Normal	Much Above Normal	Minor Flooding Possible
Gainsborough Creek	Above Normal	Much Above Normal	Minor Flooding Possible
Waskada Creek	Near Normal	Much Above Normal	No Flooding
Medora Creek	Near Normal	Much Above Normal	No Flooding
Pipestone Creek	Above Normal	Above Normal	Minor Flooding Possible
All Other Tributaries	Near Normal	Above Normal	No Flooding
INTERLAKE			
Icelandic River	Near Normal	Much Above Normal	Minor Flooding Possible
Fisher River	Near Normal	Much Above Normal	Minor Flooding Possible
All Other Streams	Below Normal	Above Normal	No Flooding
WESTLAKE			
Whitemud River and Tributaries	Near Normal	Above Normal	No Flooding
DAUPHIN LAKE TRIBUTARIES			
Valley River	Near Normal	Well Above Normal	Minor Flooding Possible
All Other Tributaries	Near Normal	Above Normal	Flooding Unlikely
NORTH			
Swan River	Near Normal	Near Normal	Flooding Unlikely
Red Deer River	Near Normal	Near Normal	No Flooding
Carrot River	Near Normal	Near Normal	No Flooding
Saskatchewan River	Near Normal	Near Normal	Minor Flooding Possible
Far Northeast	Above Normal	Above Normal	Localized Flooding is likely
Far Northwest	Above Normal	Below Normal	Flooding Unlikely
EAST			
Brokenhead River	Well Below Normal	Above Normal	No Flooding
Whitemouth River	Well Below Normal	Above Normal	No Flooding
Whiteshell	Well Below Normal	Above Normal	No Flooding

NOTE: Flooding may occur on any stream in the event of river ice buildup or ice jams.


Hudson Bay
Lake Winnipeg
N
LEGEND
ABOVE NORMAL RUNOFF
(GREATER THAN 125%)
NEAR NORMAL RUNOFF
(75% TO 125%)
BELOW NORMAL RUNOFF
(LESS THAN 75%)
DEPARTMENT OF NATURAL RESOURCES
WATER RESOURCES BRANCH
SPRING RUNOFF OUTLOOK
FORCAST DATE : MARCH 22, 1983
PREPARED BY A A W

C E W 83 03 23

Note: Forecasts based on normal weather conditions.

Province of Manitoba
Department of Natural Resources
Water Resources Branch
DAILY REPORT ON FLOOD CONDITIONS
RED RIVER 1983

* Community Dyking System
** Peak

Date APRIL 9, 1983

Location	Flow (cfs)	Stage (Feet)	Change From Yesterday (Feet)	Total Rise to Date (Feet)	Anticipated Peak Stage and Date		Flood Stage (Feet)	Dyke Design Capacity (Feet)	Previous Peak Stages and Flows			
									1978		1979	
					Stage (Feet)	Date			Flow (cfs)	Stage (Feet)	Flow (cfs)	Stage (Feet)
Winnipeg	41,500	15.45	+0.44	15.23	(ice) ** 17.34	April 7	18.0*	26.5	52,000	18.5	55,200	19.2
Below Floodway Inlet	31,500	749.97	-0.13	21.17	750-751	April 10	760	Not Dyked	43,800	752.3	48,000	752.92
Above Floodway Inlet	32,000	750.85	+0.19	21.55	753-755	April 16	760	Not Dyked	54,000	758.70	90,000	765.48
St. Adolphe	31,000	754.96	+0.60	22.93	756-758	April 15	757.5*	771	53,000	761.3	92,000	768.30
Ste. Agathe	30,000	760.30		23.76	761-763	April 15	771.8	Not Dyked	51,000	766.24	82,300	773.10
Morris	30,000	764.78	-0.46	24.19	766-768	April 14	769.4*	784	51,000	772.59	92,600	781.26
St. Jean	28,000	768.29	-0.62	25.09	769-771	April 13	771.6*	785	51,000	776.85	92,600	782.36
Letellier (includes Roseau R. Indian Res.)		N/A			774-776	April 13	780.1*	788	51,000	782.29	95,000	785.44
Emerson	25,500	777.99	+1.22	27.61	778-779	April 12	783.2	793	50,200	786.83	92,900	791.27
Drayton	23,500	30.88	+1.14				32.0	N/A	56,000	41.20	92,900	43.66
Grand Forks	9,800	22.71	-3.22		** 29.07	April 6	28.0	N/A	53,500	45.66	82,000	49.1
Halstad	4,000	10.51	-1.04				24.0	N/A	29,500	37.58	42,000	39.00
Fargo	800	14.82	-0.19		** 15.37	March 7	17.0	N/A	19,000	34.48	17,300	34.93

Weather: No significant precipitation. Gradual melting in west fringe & east Sask

ANNEX B

Province of Manitoba

Department of Mines, Natural Resources and Environment
Water Resources Division

DAILY REPORT ON FLOOD CONDITIONS-ASSINIBOINE RIVER

Observed
**Peak

Date APRIL 9/82

Location	Flow	Stage	Change From Yester-day	Total Rise To Date	Anticipated Peak Stage or Flow and Date		Existing Channel or Dyke Capacity		Previous Peak Stages and Flows			
									1970		1974	
					Stage	Date	Flow	Stage	Flow	Stage	Flow	Stage
Kamsack					1423-1425				1,460		6,700	1427.35
Shell near Inglis	100	1.12	+0.07		3.5-4.5				990	3.39	1,530	3.96
Shellmouth Inflow	200				4500 CFS	Subject			2,400	-	8,800	-
Shellmouth Level		1392.11	+0.02		1404				-	1384.42	N/A	1410.90
Shellmouth Outflow	100				100 CFS	to			1,900	-	2,300	-
Russell					1338-1339		3,000	1342.55	2,100	1340.95	2,510	1341.50
Millwood	250	1316.25	-0.58			Weather	3,000	1321.6	2,200	1322.55	2,600	1323.96
St. Lazare	1200	1277.23	+0.45		1282-1283		5,000	1283.9	3,800	1283.22	5,900	1286.26
Minjota	1250	1228.04	+0.56		1238-1240	Conditions	6,000	1240.0	5,020	1238.16	9,550	1243.04
Virden	1250	1202.71	+0.61		1214-1215		5,500	1213.5	5,000	1213.10	10,500	1216.89
Griswold	1800	1190.52	+1.18		1197-1198		5,900	1196.0	5,000	1195.89	10,500	1199.24
Brandon ~~1st St.~~ GRAND VALLEY	3000	1180.96	+0.90		1184-1185		20,000	1177.4	7,830	1171.77	10,500	1174.52
Holland	8500	971.67	+1.26		972		24,000	974.0	17,700	971.66	32,100	977.01
Portage U/S of Div.	5850	859.35	+0.05		12,000 -15,000 CFS		15,000	N/A	17,500	869.53	33,000	869.91
Portage D/S of Div.	3150				Subject to	Diversion	22,500	854.0	12,000	849.39	12,700	849.8
Baie St. Paul	3200	789.83	-0.88		** 792.95 793-794	Apr. 6	18,000	800.2	12,000	795.8	12,300	797.4
Headingley	4850	764.49	-0.57		** 765.78	Apr. 6	30,000	772.5	12,000	766.29	14,800	767.6

Province of Manitoba

Department of Natural Resources

Water Resources Branch

**Peak

DAILY REPORT ON FLOOD CONDITIONS

SOURIS RIVER 1982

Date APRIL 9, 1983

Location	Flow (cfs)	Stage (Feet)	Changes from Yesterday (Feet)	Total Rise to Date (Feet)	Anticipated Peak Stage and Date		Existing Channel or Dyke Capacity		Previous Peak Stages and Flows			
									1972		1979	
					Stage (Feet)	Date	Flow (cfs)	Stage (Feet)	Flow (cfs)	Stage (Feet)	Flow (cfs)	Stage (Feet)
Sherwood	1300	12.70	-0.30				2,140	18.0	3,210	21.57	8,400	23.95
Lake Darling	1500	N/A			OUTFLOW 2500-3000 CFS	Apr. 18	-	21.0	-	21.17	-	22.00
Minot 4NW	1200	9.37	+0.04			-	2,230	14.0	2,370	14.40	5,900	19.52
Bantry	1150	11.01	+0.29	9.43	12.5	Apr. 23	1,250	11.0	2,310	12.52	5,850	13.75
Westhope	2500	12.15	+0.02	6.30	Near F.r.E Peak 12.5	Apr. 28	150	6.3	3,050	13.30	5,800	16.22
Melita - PTH #3	3350	1406.34	-0.66	16.34	1407-1408	Apr. 14	1,300	1401.4	3,670	1406.43	6,200	1408.88
Napinka 4NE	3500	1398.29	+0.70		1400-1401	Apr. 15	1,100	1395.0	3,500	1398.51	6,100	1400.93
Hartney	3000	1380.87	-0.71		1384-1385	Apr. 17	1,700	1379.0	3,300	1382.52	6,100	1385.32
Souris	3000	1351.15	+0.38		1351-1352	Apr. 19	4,100	1351.0	3,530	N/A	6,700	1352.15
Wawanesa	3600	1148.17	+0.21	4.91	1149-1150	Apr. 21	16,500	1157.6	3,510	1148.96	6,400	1150.37

ANNEX C

WATER RESOURCES BRANCH

SPRING RUNOFF CONDITIONS AND PROSPECTS
APRIL 14, 1983

Red River

Peak stages on the Red River in Manitoba occurred between April 7 and April 12. The River remained within its banks. The James Avenue peak stage of 17.3 feet (5.285 metres) above datum occurred at 4:00 p.m. on April 7 as a result of an ice jam at the Redwood Bridge. The peak without ice was 17.0 feet (5.182 metres) late on April 9.

In recent days, levels on the Red River have been falling between one and two feet per day. The possibility of higher peak stages due to future rainfall is now quite remote. Spring weather has been generally favourable in the Red River watershed.

Assiniboine River

Spring runoff is virtually complete downstream of Brandon, but has barely begun upstream of Brandon. An instantaneous peak of about 21,000 cfs (595 m^3/s) entered the Portage Reservoir early on April 11. This resulted from a combination of flash runoff downstream of Brandon and ice action on the River between Spruce Woods and Portage la Prairie. An ice jam formed on the River just downstream of the control structure. Up to 17,000 cfs (482 m^3/s) of water was diverted into Lake Manitoba via the Portage Diversion. Diversion flows declined rapidly after April 11 due to a rapid decrease in inflows to the Portage Reservoir. By this morning, the inflow to Portage Reservoir had decreased to 8500 cfs (241 m^3/s) and the Diversion flow had been reduced

2500 cfs (70.8 m^3/s). The ice jam on the River downstream of the control structure was still in place.

Upstream of Brandon, river stages had begun to increase due to the snowmelt of April 7 to 9. However, stages have become stable or have begun to decline due to the very cool weather which began April 10. Most of the winter snow remains to be melted upstream of Brandon. River levels will rise again next week if the warm weather returns. Overbank flows are anticipated in the Virden to Griswold area. These overbank flows are not expected before April 23 at the earliest.

Souris River

Agricultural flooding from the International Boundary to Hartney began in mid-March and will likely continue until mid-May. Peak stages were observed between April 2 and April 10 before the ice had begun to move. Peak stages resulted primarily from runoff downstream of Lake Darling in North Dakota. Runoff had just begun in the Saskatchewan portion of the watershed and is now being delayed due to cool weather. The second peak from the Saskatchewan runoff will be lower than that observed last week and should reach Manitoba about May 5. Significant precipitation during the next few weeks would worsen flooding on the Souris River and would extend the period of flooding.

Interlake

There was no significant spring flooding in the Interlake. Peaks occurred a week ago.

Westlake-Dauphin-Swan River Area

Runoff had begun on the Whitemud River and on the Turtle River prior to the present cool spell. This has helped to reduce the

flood potential in the watersheds to the point where no flooding is anticipated with normal weather conditions. From the Ochre River northward to the Swan River, runoff has not yet begun and a high flood potential exists on most streams.

Red River Floodway

The floodway contained some Red River flow between April 9 and April 12. The control structure was operated from April 10 to April 12. The maximum diverted flow was about 1000 cfs (28.3 m^3/s).

Portage Diversion

The Portage Diversion was put into operation on April 5 to reduce the possibility of ice jams on the Assiniboine River downstream of Portage la Prairie. The diversion flow was increased rapidly to a maximum of 17,000 cfs (482 m^3/s) early on April 11 as a surge of water entered the Portage Reservoir behind an ice jam. The ice jam re-formed on the River downstream of the control structure. This jam dramatically raised water levels downstream of the structure, caused power outages and damaged property. This problem was alleviated by diverting more water toward Lake Manitoba. Inflows to the Portage Reservoir are much decreased and are now falling. The ice jam downstream of the structure is still in place.

Weather

Spring weather has been generally favourable. There has been little precipitation and a fairly gradual snowmelt. Indications are that there will be little or no precipitation for the next three to four days. There will be a gradual moderation of temperatures in the next few days, but active snowmelt in western Manitoba is unlikely to start before Sunday, April 17.

HYDROLOGIC FORECASTING IN SASKATCHEWAN

INTRODUCTION

Saskatchewan's physiography varies from predominantly prairie in the south to Canadian Shield in the north. Approximately 12 per cent of the province's area is covered by water, most of which is concentrated in the northern section of the province (see Figure 1). The climate in the province varies from semi-arid in the southwest to sub-humid in the central parkland region and northern areas.

The southern half of the province, which is home to most of the population, experiences mean annual precipitation of 300 to 400 mm of which about 30 per cent falls during the late fall, winter and early spring in the form of snow. Since the normal evaporation rate for the southern part of the province exceeds the normal precipitation, effective management of the water resources of the province, especially the water which accumulates as snow and then runs off in spring, is very important. Water must be efficiently stored in reservoirs when possible and landowners and communities along the streams must be warned of flood hazards since the majority of the annual flow in streams in southern Saskatchewan occurs during the two to four week spring runoff period.

When the water has been stored it is also necessary to provide an operation planning function in conjunction with a continued streamflow forecasting service to ensure that as many demands as possible (i.e. municipal, irrigation, recreation, etc.) can be met.

Superimposed on this semi-arid, sub-humid region are the North and South Saskatchewan Rivers. These rivers, with headwaters in the eastern slopes of the Rocky Mountains, are the largest in southern Saskatchewan and are used by the Saskatchewan Power Corporation (SPC) to generate electricity at two locations - Squaw Rapids and Gardiner Dam (Lake Diefenbaker) - and by many other users such as agriculture (irrigation and stockwatering), municipal and industrial water supply, recreation, transportation and commercial fishing. The construction of the Squaw Rapids Dam to create Tobin Lake and Gardiner Dam and the Qu'Appelle Dam to create Lake Diefenbaker greatly enhanced the water use potential in the Saskatchewan River Basin in Saskatchewan. To make best use of this major resource hydrologic forecasting and operation planning is essential.

Northern Saskatchewan has the majority of the province's water and very little development. There is one hydroelectric station on the Churchill River at Island Falls and a control structure for flow regulation at the outlet of Reindeer Lake. This system has been in place for over 50 years. With increased mineral exploration and development and possible further hydroelectric development streamflow forecasting in northern Saskatchewan will become increasingly important.

FORECASTING SERVICE

The streamflow forecasting service in Saskatchewan is provided by the Hydrology Branch of Saskatchewan Environment and comprises two major components:

1. Spring runoff forecasting; and
2. Water supply and short-term streamflow forecasts.

Spring runoff forecasting is carried out on rivers, multi purpose lakes and cooling reservoirs for thermal electric stations in the province where justified by the need for flood warning and water supply management. Forecasting begins each year with a runoff outlook published on February 1 which describes antecedent precipitation conditions prior to freeze-up, winter precipitation to date and the outlook for runoff in the various areas of Saskatchewan. Detailed forecasts are issued bi-monthly from March 1 until the runoff commences and include forecasts of peak mean daily flow, spring runoff volume and peak water level for 24 streamflow points, as well as forecasts of peak lake levels for 17 recreation and multi-purpose lakes and reservoirs (see Figure 2). Once runoff begins forecasts are updated as recorded flows become available.

Water supply and short-term streamflow forecasting is carried out in the Saskatchewan, Qu'Appelle and Churchill River Basins on an ongoing basis. When required by unusual high flow events this service is extended to other basins. Operation planning on reservoirs and recreation lakes is also conducted in this program. In this paper the program on the Saskatchewan River system will be described in more detail than the other systems.

Forecasting on the Saskatchewan River system involves monthly water supply forecasts which predict streamflow volumes for from two to eight months and describe proposed operations for Lake Diefenbaker and Tobin Lake. Each week river flow forecasts are issued for the next nine days for the North

and South Saskatchewan Rivers. These forecasts are for mean daily flows and also include planned operations of Lake Diefenbaker and Tobin Lake. During times of high flow river flow forecasts are updated daily and operation plans are adjusted accordingly.

ORGANIZATION

The Operations Division of the Hydrology Branch is responsible for the forecasting service in Saskatchewan. The Division develops forecasting equations, updates and maintains existing forecasting models, collects hydrometric data at special purpose stations and monitors streamflow and meteorological conditions on a year round basis. The Division also conducts year round forecasting and provides the operation planning function on the Saskatchewan, Qu'Appelle and Churchill River systems. An organization chart for the Hydrology Branch is shown on Figure 3.

During the spring runoff period staff from the other divisions in the Hydrology Branch become involved in the monitoring and forecasting activity. Engineers from the Investigations Division are assigned as Basin Engineers to specific river basins and have technicians assigned to assist them in forecast preparation. Basin Engineers and technicians are usually assigned to the same basins each year so that they become familiar with the basins' hydrologic conditions and flood hazard areas. The Head of the Operations Division assumes the role of Runoff Co-ordinator and is responsible for co-ordination of field and office activities and issuing forecasts after consultation with the Basin Engineers. The organization chart for spring runoff forecasting is shown on Figure 4.

The forecast centre, situated at Saskatchewan Environment's office in Regina, is the gathering point for all input for forecasting. Forecasts are issued from this office; final forecasts are reviewed and approved by the Runoff Co-ordinator. When a high runoff is expected Basin Engineers occasionally set up field offices in the basins to aid in data collection, analysis and forecast information dissemination.

INPUT FOR FORECASTS

Hydrometric Data

The majority of the hydrometric data used in forecasting in Saskatchewan is collected by Water Survey of Canada (WSC) under the federal-provincial hydrometric agreement. WSC stations in Alberta are used to monitor upstream flows in the Saskatchewan River system.

Gauge readers are the major source of real time data for spring runoff forecasting. Each spring about 50 individuals read the gauges at WSC stations on a once per day frequency or more often if required. The annual cost of the gauge readers is about $8,000.00.

Telemarks are installed at most mainstem stations on the Saskatchewan River system and at a few other key stations in other Saskatchewan basins. Most of the monitoring of Saskatchewan River system stations in Alberta is done by WSC in Calgary who call the key telemarks each morning and telex the gauge heights and flows to interested agencies. The Hydrology Branch calls telemarks manually when data is required at an increased frequency.

Recently the Hydrology Branch purchased six Bristol Data Collection Platforms (DCPs) which are installed in the Saskatchewan and Qu'Appelle

River systems. These DCPs measure the water level at WSC stations and transmit hourly data every three hours. The data is accessed with an IBM PC micro-computer using a telephone dial up to the National Earth Satellite Service (NESS). At the present time the handling of the data from DCPs is done manually in the same way as gauge reader and telemark input. Plans are in place to develop an automated data handling system for DCP data using the IBM PC.

When the Hydrology Branch purchased the DCPs to improve remote location data collection land line based systems were also considered. One of the advantages of the DCP over a land line system is that DCPs can be moved relatively easily from one location to another while land line systems can not. Thus DCPs used for operation planning during the summer and fall can be moved to key spring runoff stations for the short time runoff is in progress and information for both uses can be supplied with one DCP.

Water level observations are entered into a book in the forecast centre, the most recent shift adjustment is applied and a flow is interpolated from stage discharge tables. WSC transmit metering data to the forecast centre when it becomes available. During spring runoff WSC use a computer program to document meterings and the previous day's measurements are transmitted to the forecast centre each day. For the remainder of the year metering data are sent by telephone.

The Hydrology Branch operates several special purpose hydrometric stations in Saskatchewan. These stations are located at sites where continuous records are not required but where real time information is very useful to

aid in forecasting during relatively short duration flooding events. Hydrology Branch technicians meter at these sites and gauge readers call in gauge readings at the required frequency. The technicians also perform an important function by observing snowmelt, streamflow and ice conditions and notifying the forecaster. During the spring runoff event this information is crucial in revising forecasts.

Meteorological Data

Data collected at Atmospheric Environment Service (AES) stations are used exclusively to monitor precipitation in the province. The synoptic stations are most useful for ongoing monitoring since data is available on a real time basis through AES. Climatological stations are used especially prior to the spring runoff event to document the winter precipitation in the various basins and to fill in the gaps in the synoptic station network. Since no snowmelt models are used in Saskatchewan, temperature data are not gathered from climatological stations and are used in a qualitative way when available from synoptic stations. Hydrology Branch staff telephone AES Climatological Services when precipitation data is required.

Weather forecasts published by AES are used in a qualitative way in streamflow forecasting. Since the main determining factor in the magnitude of the spring runoff is the accumulated water in the snowpack, recorded meteorological events, not forecast ones, are used to update spring runoff forecasts. In the Saskatchewan River system, rainstorms in May, June and July often cause high runoff. Meteorological forecasts are useful in warning the streamflow forecasters of a possible change in hydrologic

conditions in the basin. The streamflow forecaster can then be prepared to monitor the effects of the meteorological event and adjust the forecast accordingly.

The Hydrology Branch measures the snow depth and water equivalent in mid-February and mid-March at 100 snow courses in the Qu'Appelle, Souris, Wood and South Saskatchewan River Basins. The data from these snow surveys are used in some regression equations for spring runoff forecasting but are used primarily as a check on the accumulated precipitation data from the climatological network and to estimate snowpack losses. This exercise also permits the Hydrology Branch technicians to observe the areal extent of snow cover, snow pack conditions (i.e. existence of ice lenses), the degree of snow drifting, the snow cover by the various types of land use (i.e. stubble, summerfallow, pasture) a qualitative estimate of soil moisture conditions and the amount of snow in the river channels at key locations. Alberta Environment measure snow depth and water equivalent at snow courses in the headwaters of the North and South Saskatchewan Rivers in the late winter and early spring. This data is transmitted to Saskatchewan Environment and is used in a qualitative way in water supply forecasting.

Remote sensing of the snowpack in the Souris River Basin is done routinely by U.S. National Weather Service (NWS) aircraft with a gamma sensor. Ground truth work is not needed for this program and water equivalent estimates are available for the various flight lines the next day from NWS. A joint Canada-United States project to measure snow water equivalent is currently being conducted in Saskatchewan using gamma and radar technologies. When required the Hydrology Branch provides ground truth data for this project. This data is not available on a real time basis.

FORECAST GENERATION

Spring Runoff

Multiple regression models are the main tools used to generate spring runoff forecasts and are generally of the form:

Spring Runoff Volume = AX + WY + Z

where X, Y and Z are constants, A is the antecedent precipitation in the basin and W is the winter precipitation in the basin. The antecedent period used is from August 1 to October 31 while the winter period is from November 1 to April 1. When forecasts are generated before the end of March normal precipitation is used to complete the winter period and produce the forecast. Forecasts for peak flows are also generated with equations of this form.

One of the main problems with this type of equation is that snowpack losses are not considered. The forecaster therefore compares snow survey results to the winter precipitation values and adjusts the results accordingly. Another problem is encountered when there is high antecedent precipitation, but low winter precipitation. The equations may predict an above normal runoff when in fact there is very little or no snow on the ground. For these reasons the forecaster relies on visual confirmation of snowpack conditions from technicians, AES climate observers and WSC.

These equations have been found to be sufficiently accurate for spring runoff forecasts generated well in advance of the beginning of the snowmelt. The type of snowmelt (rapid, slow, north to south, etc.) and

precipitation during the snowmelt have a major influence on the runoff and thus these equations cannot be expected to account for all factors influencing the runoff event. When the runoff has commenced the forecasts generated by the equations are adjusted if the type of runoff and recorded flows indicate that a higher or lower than forecast runoff event is occurring. Forecast equations for spring runoff are updated approximately every eight years.

Saskatchewan River Basin Water Supply Forecasts

Regression models are also used for forecasting water supply on the Saskatchewan River system. For the fall and winter periods the serial correlation from one month's flow to the next is quite high and thus winter water supply forecasts are generated using this type of relationship. For spring and summer water supply forecasts, multiple linear regression equations developed by the Prairie Provinces Water Board (PPWB) are used. These equations use various factors such as winter natural flow, winter precipitation or snow water equivalent, runoff season precipitation and an index of prairie snow melt runoff which predicts mountain snowpack losses. The result is the total natural streamflow volume for the inflow to Lake Diefenbaker (South Saskatchewan River) and the North Saskatchewan River at Prince Albert for the March to October period.

Water usage in the Saskatchewan River Basin in Alberta has increased since the area was first settled and streamflow records reflect these increased usages. The flow records must be converted to "natural" flow conditions by adding water used and subtracting water added to the system before forecast equations can be developed. When the forecasts are generated the natural

flows are adjusted to reflect normal uses, diversions and releases. For the spring and summer water supply forecasts the total March to October volume forecast is divided by a normal monthly distribution of streamflow to get a forecast of mean monthly streamflow.

The results from the equations are adjusted by the forecaster especially later in the summer forecast period (July to October) when the serial correlation of one month's flow to the next becomes a factor. These equations were developed in the early 1970s and are now being updated by Saskatchewan Environment.

Streamflow Forecasting

Streamflow forecasting on the Saskatchewan River system is done by routing recorded upstream flows using lag times and manual adjustments for local inflow, ice conditions, evaporation and diversions. A routing model (SIMPAC) is now being tested in this basin to determine whether the results are as accurate as the manual methods now used and whether the model is as efficient in terms of time spent by the forecaster. The travel time from the furthest upstream points to the Saskatchewan-Alberta boundary is from three to eight days, depending on flows, and on each stream there are intermediate hydrometric stations to check the accuracy of forecasts and to allow for adjustments to lag times and local ungauged inflows.

During the spring runoff event streamflow forecasts are made on the small Saskatchewan streams using lag times and past experience with ungauged inflows. Routing models (SIMPAC and SSARR) have been calibrated in some basins and are used in high flow years. The models are also used to handle

basin study work. The forecast of timing of peak flows is usually on a daily basis, but in some instances when control structure operations are involved hourly forecasts may be made.

COMMUNICATIONS

Spring runoff forecasts are issued as Department News Releases and as mailings to individual users. These users include other provincial departments and agencies, rural municipalities, urban municipalities, power and telephone companies and the Provincial Emergency Measures Organization. When runoff is in progress, the Assistant Director of the Hydrology Branch assumes the Information Dissemination role and handles all media contact on runoff while contacts for technical information are through the Runoff Co-ordinator.

Forecasts for the Saskatchewan River system are routinely sent to users as indicated above plus Manitoba Hydro, irrigators and other water users along the South Saskatchewan River. When a major change in the release pattern below Lake Diefenbaker is planned all users from the lake to the junction with the North Saskatchewan River are notified by telephone. Media contact for forecasts for this basin are through the Head of Operations Division.

SUMMARY

The forecasting program has been evolving in Saskatchewan for the past 15 years and has undergone many changes. Forecasting models have improved as more hydrometric data is collected and techniques for evaluation and equation development improve. Resource development and increased urban development in flood prone areas has increased the demand for the flood

forecasting service. With the Operations Division concentrating on the forecasting and operation planning program and the Investigations Division providing support in high spring runoff years, the Hydrology Branch has been able to meet the users needs and develop improved forecasting methods.

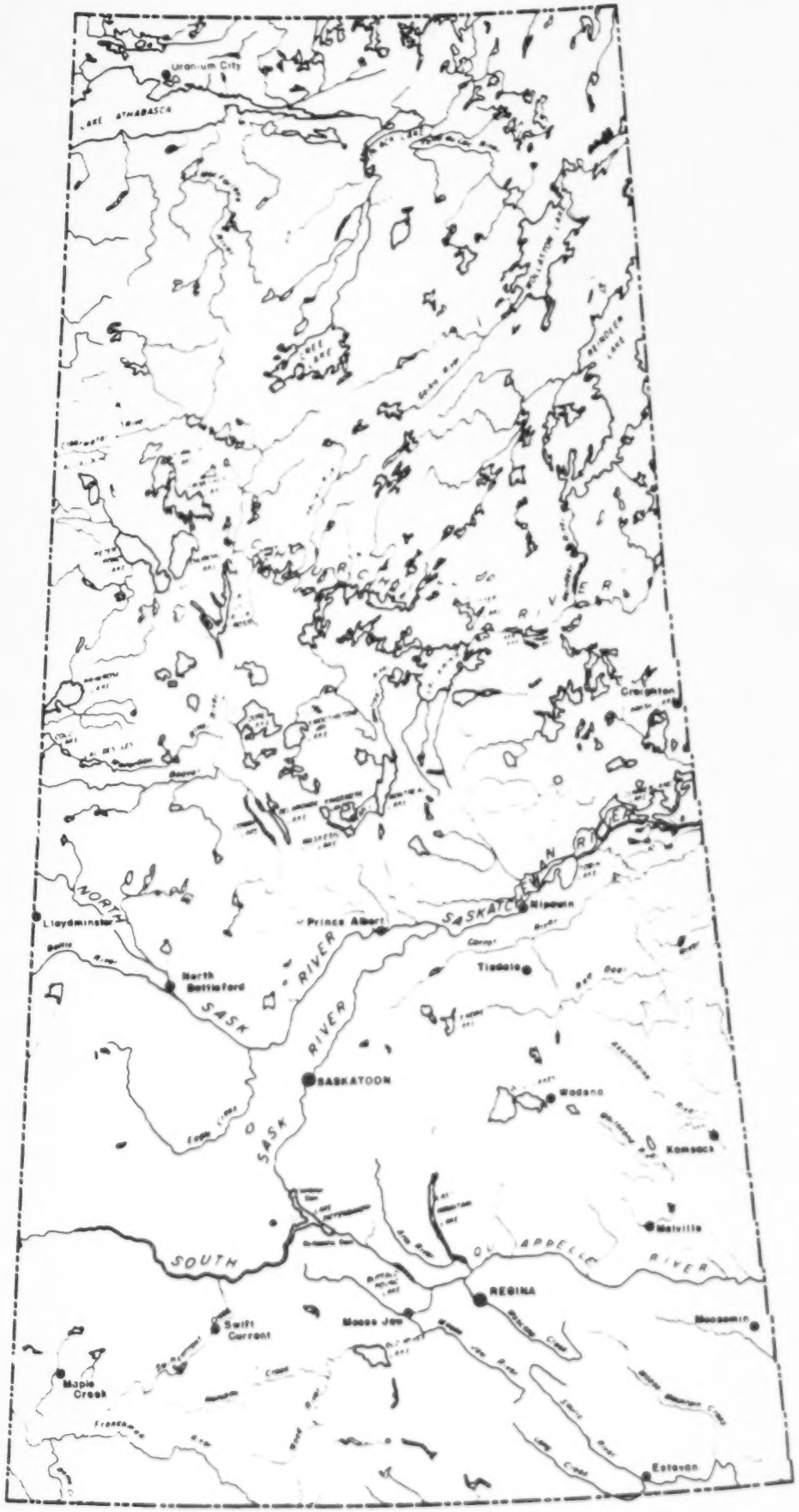

Uranium City
LAKE ATHABASCA
Creighton
Nipawin
Prince Albert
Lloydminster
North Battleford
Tisdale
SASKATOON
Wadena
Kamsack
Melville
REGINA
Moose Jaw
Swift Current
Maple Creek
Estevan
NORTH SASK RIVER
SASKATCHEWAN RIVER
SOUTH SASK RIVER
QU'APPELLE RIVER

Figure 1

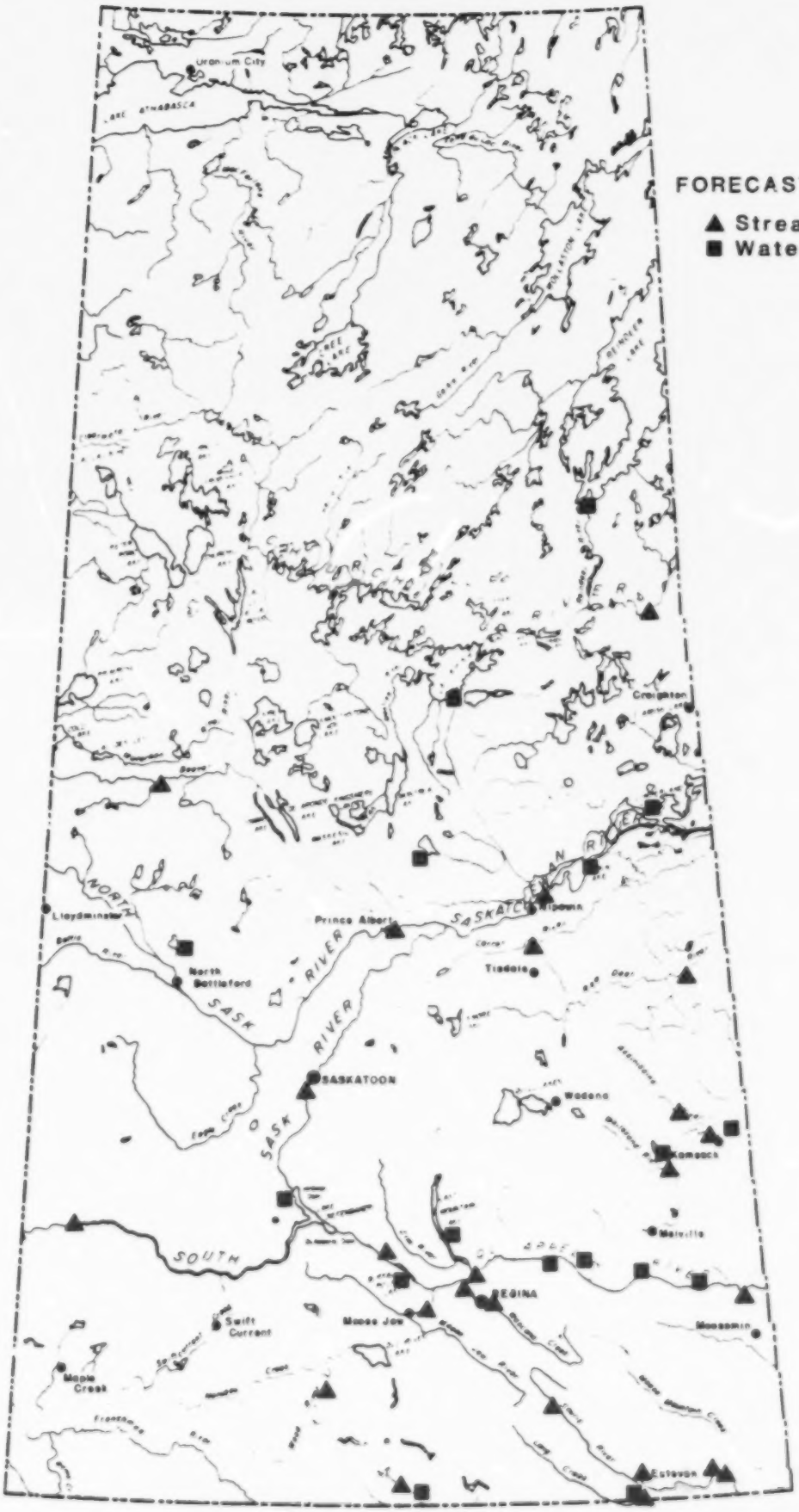

FORECAST POINTS
▲ Streamflow
■ Waterlevel
Uranium City
Lloydminster
North Battleford
Prince Albert
Tisdale
Creighton
SASKATOON
Wadena
Melville
REGINA
Swift Current
Moose Jaw
Maple Creek
Estevan
Moosomin
SASK RIVER
SOUTH SASK RIVER
SASKATCHEWAN RIVER
QU'APPELLE

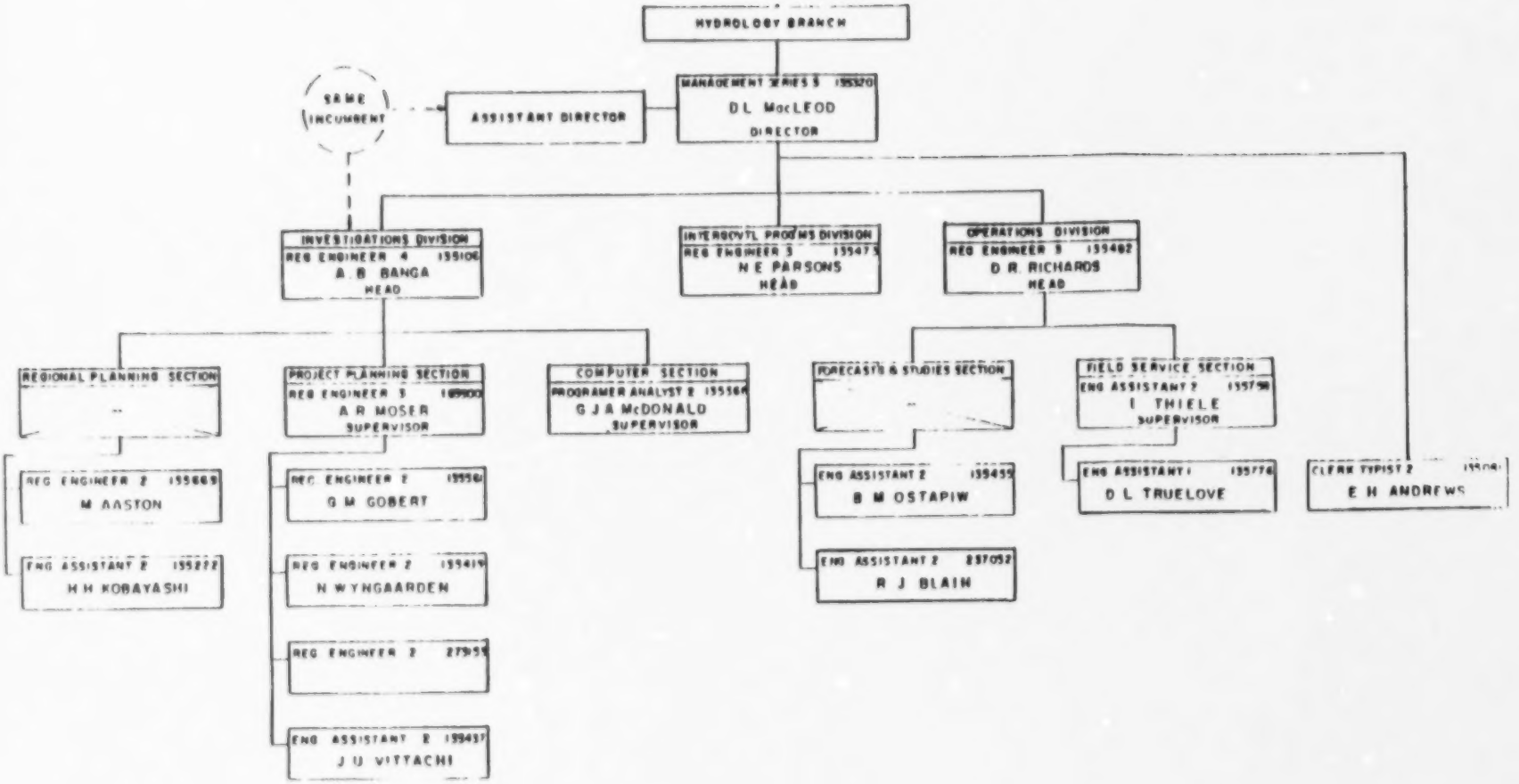
Figure 2

Figure 3

Saskatchewan Environment

Hydrology Branch

Organization



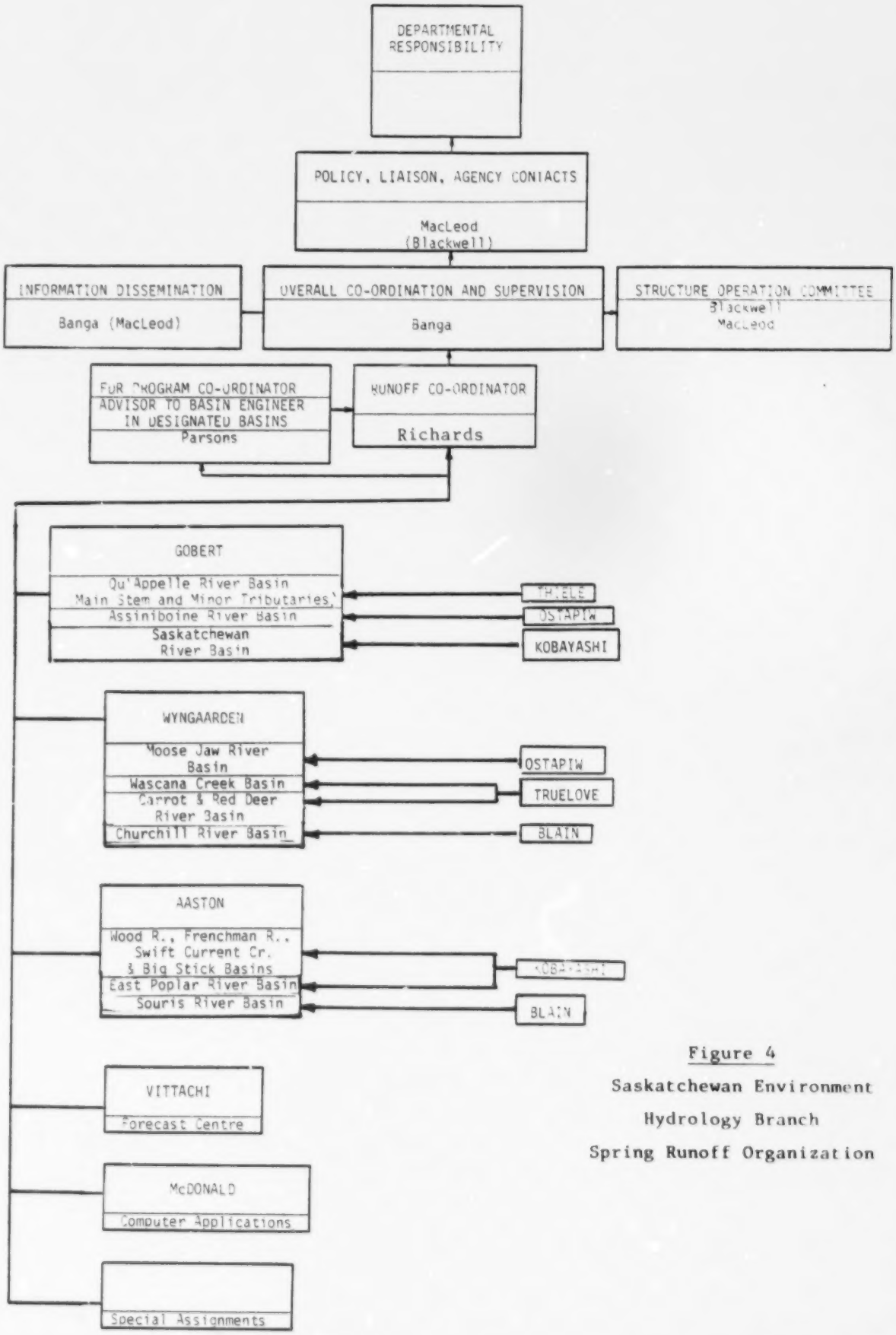


Figure 4

Saskatchewan Environment

Hydrology Branch

Spring Runoff Organization

SPRING FLOOD FORECASTING FOR MAYO

and ROSS RIVER, YUKON TERRITORY

prepared for:

TECHNICAL WORKSHOP ON STREAMFLOW FORECASTING

Toronto, Ontario

November 22 - 24, 1983

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October 1983

INTRODUCTION

A simple flow forecasting model originally developed in 1976 by Verschuren and Crawford and modified by Department of Indian Affairs and Northern Development, Whitehorse staff, provides adequate flood warning for the Yukon communities of Ross River and Mayo. The snowmelt model which is based on the degree day method, provides five day estimates of maximum daily discharge utilizing five day weather forecasts and recorded discharge, temperature and precipitation inputs for previous days. The model has been shown to estimate the timing and magnitude of peak flow events with reasonable accuracy providing advance warning for dike reinforcement and implementation of emergency measures.

SETTING

This paper summarizes the development of the model and its application to the 1983 freshet. The area of concern drains the western slopes of the Selwyn Mountains in the central eastern portion of Yukon Territory (figure 1). The Pelly River upstream of the community of Ross River has a drainage area of 18 000 square kilometers. Elevations of the basin range from 700 to 2 700 meters with a median elevation of 1 160 meters. The basin is heavily forested in the lower elevations with black and white spruce and some lodgepole pine and apsen. Alpine fir dominates treeline elevations which is located at 1 350 to 1 500 meters. Mean annual temperature and mean May to September temperatures are -7 and 9 degrees respectively. Mean annual precipitation is 253 millimeters with approximately 60 percent as snowfall.

The nearby Stewart River basin is similiar with respect to physiography. The drainage area of the basin above Mayo is 31 300 square kilometers. Elevations range from 485 meters at Mayo to 3 000 meters with a median elevation of 2 020 meters. Mean annual and mean May to September temperatures are -4 and 11 degrees respectively. Mean annual precipitation is 293 millimeters with approximately 60 percent as snowfall. Peak flow events in both systems are in response to spring snowmelt usually in early June. Both communities are located in the floodplain and are susceptible to flooding at frequent intervals.

FIGURE 1

YUKON TERRITORY
WITH PELLY RIVER BASIN AND
STEWART RIVER BASIN

MODEL DEVELOPMENT

The choice of a technique to form the basis for model development was made upon consideration of the available techniques, the degree of accuracy required, the variability of the basin under study, and the available data base. The latter was found to be the limiting factor. As many northern areas, Yukon Territory can be considered a sparse data region. Though hydrometric coverage in some areas is adequate, the meteorologic network is less dense. The limited nature of input information for model development restricted the selection of a suitable technique. A model based on a temperature index method was found most appropriate.

Snowmelt is a thermodynamic process governed by the heat exchange between the snowpack and the atmosphere and ground surface. There are six individual components contributing to the theromdynamic process which include energy inputs from: shortwave radiation, longwave radiation, convection, condensation or evaporation, geothermal heat, and the heat content of rainfall. To monitor each process would provide and excellent understanding of the overall snowmelt process and would provide input to a sophisticated simulation model.

Air temperature provides the single best index of snowmelt. Some of the above terms may be combined in such a way as to yield a simplified surface heat transfer relationship based on the temperature gradient between the atmosphere and the snow surface. The degree day method is such a simplified technique which has been shown to produce reasonable estimates of snowmelt. The general form of the degree day equation is:

$$M_s = c(T_a - T_b)$$

where: M_s = snowmelt (cm)
T_a = maximum daily air temperature (^oC)
T_b = base temperature (^oC)
c = snowmelt coefficient

The value of the base temperature (T_b) is generally 0^oc and represents the point below which no melting occurs. This may sometimes be higher or lower to relect the difference between the measured temperature and the temperature at the snow surface. The snowmelt index is the degree day factor (DFF) which is defined as the depth of snowmelt leaving a basin as streamflow per degree day:

$$DFF = \frac{\text{Volume of snowmelt}}{\text{Number of degree-day}}$$

The degree day factor changes throughout the season in response to the progression of the snowpack through the various stages of metamorphism. Its value is generally low at the beginning of the season since the temperature of the pack must be raised to 0 degrees prior to snowmelt. It increases in magnitude as the snowpack becomes saturated and each incremental amount to melt contributes to runoff. The value again decreases as the snowpack becomes depleted and no longer continuous in extent.

For model development purposes it was necessary to make several simplifying assumptions. Since air temperature generally varies inversely with elevation it is common practice, for the application to such techniques, to partition a basin into regions of uniform temperature. If sufficient instrumentation to produce detailed temperature profiles are lacking, partitioning is generally based on elevation contours and the environmental lapse rate which is applied to these to approximate the variation in temperature with elevation. A value of 2.2 degrees per 300 meters was found to be most appropriate after experimentation with this parameter. The temperature in each elevation band was assumed to be constant.

At the time the model was developed no snow course information was available for the area of concern. It was assumed for model purposes that the snowpack density was 0.1. The annual maximum snowpack for input to the model, is determined by the summation of individual snowfall amounts over the accumulation season. This does not account for evaporation or losses due to other sources. It is also assumed that the snowpack is uniform throughout the basin. This may be a major deficiency since precipitation generally increases with elevation and the only available climate information is for valley bottoms.

Rainfall occuring during the melt season may have varying effects depending on the condition of the snowpack. The heat content of rainfall generally produces little melt. It is the rainfall inputs itself which contribute to the runoff process. Before runoff from the snowpack occurs the cold content of the pack must be removed by raising its temperature to 0 degrees, voids in the pack must be filled, and the rain or meltwater must travel through drainage channels to the bottom of the pack. Rainfall inputs may either freeze, releasing latent heat, go into storage to satisfy water deficiencies or travel through the pack producing runoff.

Due to the simplicity of the model it was not possible to account for specific affects of rainfall inputs. The amount of additional melt produced by the rainfall is determined and the rainfall input itself is considered as water equivalent only adding to the available snowpack.

The lag times of each respctive elevation band use initially crudely estimated, These were then manipulated in such a way as to optimally reproduce recorded streamflow.

Initially a series of values representing the seasonal variation of the degree day factor were determined using historical recorded mean values. Though results were satisfactory for average years, inconsistencies became evident when these values were applied to data for abnormal years such as years which had a early warm spell followed by cooler weather. As a result of this observation it was desirable to include an updating factor in the model.

Two daily computed adjusting factors were used to provide the update. The ratio of the estimated and recorded discharge for the previous day reflects the model's ability to estimate flows and the ratio of recorded flows of consecutive days provide an indication of the climatic trend. The product of these two ratios is used to update the degree day factor.

The model requires daily inputs of recorded flow, actual maximum daily temperature, total daily precipitation, and five day estimates of temperature and precipitation.

The main steps of the model are as follows:

1) determines the temperature of each elevation band using the environmental lapse rate.

2) calculates the number of degree days for each elevation band by substracting base temperature.

3) calculates snowmelt for each band by multiplying number of degree days by the updated degree day factor.

4) estimates rain melt for each elevation band and adds precipitation to available snowpack.

5) determines streamflow produced by each elevation band by applying the appropriate lag time.

6) determines total streamflow at the point of interest.

7) calculates daily updating factor.

1983 SPRING FLOOD

The described model, a very simple representation of a complicated process has been found to provide reasonable flow estimates of peak flows and the associated water levels. This permits the two communities adequate advance warning and the Emergency Measures Organization to prepare for action.

The 1983 freshet produced peak flows of 1 510 m^3/s and 2 860 m^3/s at Ross River and Mayo respectively. These flows represent the fourth and fifth highest recorded during the 28 and 34 years of record. Unseasonably record high temperatures during the latter part of May on a slightly above average snowpack produced the peak flows.

The flood damage potential at Ross River is not high since the greater part of the community, with the exception of a few buildings, is situated on high ground. A dike protects part of the community though the few buildings mentioned are located near the downstream end of the dike. The river rose 1.5 meters in 10 days causing only minor damage to the few properties in the low lying area. A car ferry and footbridge providing access to the North Canol Highway were closed for several days during the high water period.

The situation is considerably more critical at Mayo which is surrounded by a high dike along the river bank. If the dike were overtopped, almost the entire community would experience some flooding and extensive damage. The 1983 flood season saw the Stewart River rise 3.6 meters in six days and come within .3 meters of the top or the dike. Advance warning, indicating that river stage would reach the top of the dike before receding, was provided several days prior to the peak. Though the daily estimated values were slightly higher than the recorded, a change in weather conditions could have produced flood stages. A flood warning was issued permitting the Emergency Measures Organization to mobilize. As the flood waters approached the top of the dike, work crews worked throughout the night to reinforce the dike. Preparations were made to evacuate the hospital.

As forecast, river stage peaked and began receding on the evening of June 5 (figure 2), permitting the community to relax after several tense days and nights. Since the dike was not overtopped, the only damage occured in low lying areas on the outskirts of town which were not protected by the diking system, and by the rising groundwater level which caused flooding in several basements behind the dike.

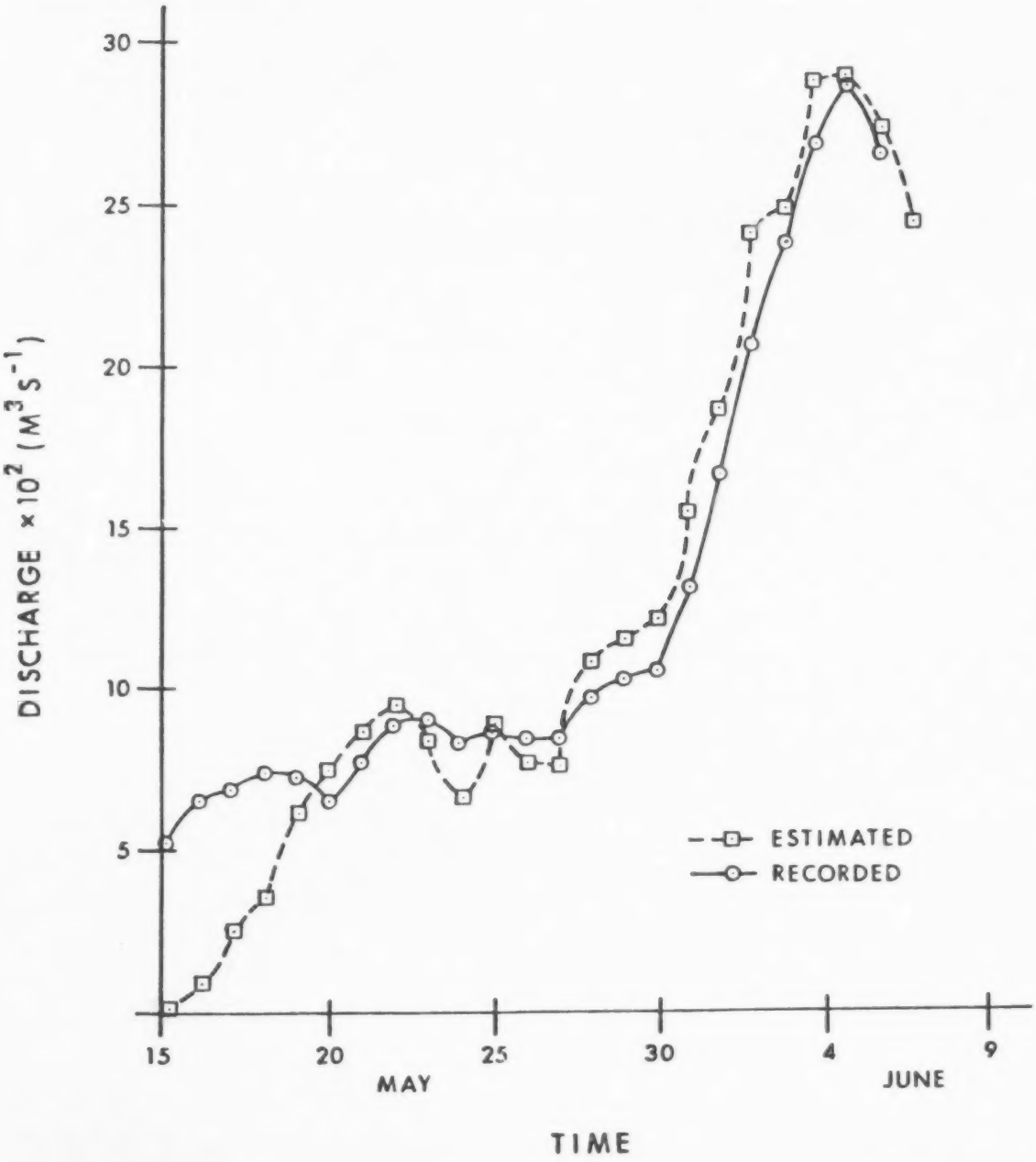
CONCLUSION

The simple temperature index snowmelt model described here has been shown to reliablely predict peak flood levels several days in advance, thus providing ample warning for the communities in question, and for the Emergency Measures Organization to prepare for the event. Only minimal inputs of actual temperature, precipitation, and discharge and five day forecasts of temperature and precipitation are required. The resulting estimates of peak flows have been reasonably accurate with respect to both magnitude and timing.

REFERENCE

Verschuren, J.P. and D. Crawford. Spring Flood Forecasting For Mayo And Ross Rivers, Yukon Territory. Department of Civil Engineering, The University of Alberta, Edmonton, Alberta. April 1976.

FIGURE 2 RECORDED AND ESTIMATED STREAMFLOW
STEWART RIVER AT MAYO 1983.



U.SPORNS - B.C.HYDRO. -

WATER MANAGMENT FOR THE COLUMBIA RIVER TREATY OPERATION.

THE COLUMBIA RIVER TREATY,WHICH PROVIDES FOR CO-OPERATIVE DEVELOPMENT OF THE WATER RESOURCES OF THE COLUMBIA RIVER BASIN, WAS SIGNED IN WASHINGTON , D.C. ON 17. JANUARY 1961 BY REPRESENTATIVES OF THE UNITED STATES AND CANADA.

ANNEX A OF THE TREATY DESCRIBES THE PRINCIPLES OF OPERATION, BOTH FOR FLOOD CONTROL AND HYDROELECTRIC POWER.OF PARTICULAR INTEREST FOR WATER MANAGEMENT IS PARA 2.OF ANNEX A , WHICH READS AS FOLLOWS :

"A HYDROMETEOROLOGICAL SYSTEM , INCLUDING SNOW COURSES , PRECIPITATION STATIONS AND STREAMFLOW GAUGES WILL BE ESTABLISHED AND OPERATED, AS MUTUALLY AGREED BY THE ENTITIES AND IN CONSULTATION WITH THE PERMANENT ENGINEERING BOARD, FOR USE IN ESTABLISHING DATA FOR DETAILED PROGRAMMING OF FLOOD CONTROL AND POWER OPERATIONS. HYDROMETEOROLOGICAL INFORMATION WILL BE MADE AVAILABLE TO THE ENTITIES IN BOTH COUNTRIES FOR IMMEDIATE AND CONTINUING USE IN FLOOD CONTROL AND POWER OPERATIONS."

IT SHOULD BE NOTED, THAT THE TREATY COVERS ONLY WATER MANAGEMENT FOR THE BENEFIT OF FLOOD CONTROL AND POWER, AND NOT FOR SUCH THINGS AS FISH AND WATER QUALITY.

IT SHOULD FURTHER BE NOTED, THAT PARA 2. SPECIFIES HYDROMET DATA TO BE MADE AVAILABLE TO THE ENTITIES IN BOTH COUNTRIES "FOR IMMEDIATE AND CONTINUING USE", WHICH MEANS TRANSMISSION OF REAL-TIME DATA AROUND THE CLOCK.NONE OF THE ENTITIES HAS AS YET LIVED UP TO THIS TERM OF THE TREATY, HOWEVER GREAT EFFORTS ARE BEING MADE TO IMPLEMENT A REAL-TIME DATA EXCHANGE PROGRAM.

WITHIN CANADA SPECIAL AGREEMENTS WERE SIGNED BETWEEN THE GOVERNMENTS OF CANADA AND BRITISH COLUMBIA COVERING DETAILS FOR THE IMPLEMENTATION OF THE TREATY.UNDER THESE AGREEMENTS THE PROVINCIAL GOVERNMENT AIDED IN THE ESTABLISHMENT OF A SNOWCOURSE NETWORK IN THE CANADIAN PORTION OF THE COLUMBIA RIVER DRAINAGE.THE CANADIAN WEATHER SERVICE PROVIDED THREE AUTOMATIC HIGH LEVEL WEATHER STATIONS TO SUPPLEMENT ITS CLIMATOLOGICAL NETWORK IN THE AREA, CONFINED ALMOST ENTIRELY TO VALLEY STATIONS. IN ORDER TO PROVIDE REAL-TIME DATA FROM THESE CLIMATOLOGICAL STATIONS,WHICH NORMALLY REPORT ONLY ONCE A MONTH BY MAIL,AES ARRANGED FOR DAILY TELEPHONE REPORTS.WATER SURVEY OF CANADA TOOK ON THE RESPONSIBILITY TO INSTALL AND MAINTAIN CERTAIN STREAM GAUGES AND RESERVOIR GAUGES CONSIDERED TO BE PART OF THE "TREATY" NETWORK.

A RELIABLE COMMUNICATIONS SYSTEM WAS REQUIRED TO PROVIDE REAL-TIME HYDROMET DATA TO THE COLUMBIA RIVER TREATY ENTITIES IN BOTH COUNTRIES FOR THE DAY TO DAY WATER MANAGEMENT OPERATIONS.IN CANADA BC HYDRO'S VHF/UHF INTERNAL COMMUNICATIONS SYSTEM WAS UTILYSED FOR THIS PURPOSE.A LINK TO THE WEATHER TELETYPE SYSTEM PROVIDED THE DATA ORIGINATING WITH AES,AND REGULAR TELEPHONE SERVICE WAS USED TO INTERROGATE SOME HYDROMETRIC STATIONS.THE DATA EXCHANGE BETWEEN THE ENTITIES IN THE TWO COUNTRIES WAS ACCOMPLISHED BY MEANS OF A PRIVAT TELETYPE SYSTEM OWNED BY THE US CORPS OF ENGINEERS.

RECENTLY DATA MANAGEMENT IN BOTH COUNTRIES HAS BEEN UNDERTAKEN BY LARGE COMPUTER SYSTEMS, THE CROHMS SYSTEM IN PORTLAND , OREGON, AND A VAX DISTRIBUTED PROCESSOR AT BC HYDRO'S SYSTEM CONTROL CENTRE ON BURNABY MOUNTAIN.BOTH COMPUTER SYSTEMS ARE PERMANENTLY LINKED BY MICROWAVE AND FULL AUTOMATION OF A REAL-TIME DATA EXCHANGE BEWEEN THE TWO ENTITIES SHOULD BE IN OPERATION BY THE END OF 1983.VHF/UHF TELEMETRY FROM REMOTE SITES AT BC HYDRO HAS BEEN REPLACED BY SATELLITE TELEMETRY (DCP) FOR GREATER EFFICIENCY.

DAY TO DAY WATER MANAGEMENT OF THE THREE CANADIAN COLUMBIA RIVER TREATY RESERVOIRS MICA, ARROW AND DUNCAN IS GUIDED BY A NUMBER OF RESERVOIR RULE CURVES.EACH RULE CURVE HAS A SPECIFIC OBJECTIVE AND SPECIFIES A MONTH-END TARGET RESERVOIR LEVEL.

THE FLOOD CONTROL STORAGE RESERVATION CURVE SPECIFIES MAXIMUM MONTH-END RESERVOIR LEVELS WHICH WILL PERMIT EVACUATION OF THE RESERVOIR TO CONTROL PREDICTED INFLOWS TO BELOW FLOOD DAMAGE LEVELS.THIS RULE CURVE HAS PRIORITY DURING FLOOD CONTROL PERIODS.THE REQUIRED DAY-TO-DAY RESERVOIR RELEASES ARE DETERMINED WITH THE AID OF THE SSARR RUNOFF SIMULATION PROGRAM RUN BY THE RIVER FORECAST CENTER PORTLAND.

THE CRITICAL RULE CURVE SHOWS MINIMUM MONTH-END RESERVOIR LEVELS WHICH SHOULD BE MAINTAINED TO MEET POWER DEMANDS UNDER THE MOST ADVERSE WATER CONDITION.(BASED ON HISTORICAL STUDIES.)

THE VARIABLE REFILL CURVE SHOWS RESERVOIR ELEVATIONS REQUIRED TO ENSURE REFILLING OF THE RESERVOIR BY THE END OF JULY EACH YEAR.THIS RULE CURVE IS BASED ON THE RESPECTIVE SEASONAL RUNOFF VOLUME FORECASTS.SUCH FORECASTS ARE ISSUED EACH MONTH STARTING IN JANUARY BY BC HYDRO'S HYDROLOGY SECTION FOR MICA , ARROW , AND DUNCAN RESERVOIRS, AND BY THE RIVER FORECAST CENTER PORTLAND FOR THE COLUMBIA RIVER DRAINAGES IN THE USA.A 95 % CONFIDENCE FORECAST IS USED FOR THE OPERATION AND CORRELATION-TYPE PROCEDURES ARE CURRENTLY BEING USED FOR THESE RUNOFF VOLUME PREDICTIONS.

BACKGROUND
OTTAWA RIVER

TECHNICAL WORKSHOP

ON

STREAMFLOW FORECASTING

Prepared by:
N. MANGIONE

Historical Background of Ottawa River

The exciting background of the Ottawa River is contained in any history book of early Canada. Before 1900, the main stream of the river and some of its tributaries served as major transportation routes. Champlain and the early explorers and fur traders in the 1600's and 1700's canoed up the Ottawa and Mattawa, portaged to Lake Nipissing, thence to the French River en route to Georgian Bay and the West. Later, the Ottawa was used to float timber and many small logging dams were built on tributaries to facilitate this use.

It was only in 1908, after the publication of a report of the proposed Georgian Bay Ship Canal, that the first of the principal works was built by the federal Department of Public Works to "control by storage of the spring floods of the Ottawa River... and to establish practically slack water navigation".[1] The total cost of the control works for Temiskaming, Quinze and Kipawa reservoirs constructed in the 1912-14 period, was less than $1 million, an investment which has since been repaid a great many times. These three reservoirs, originally built for navigation purposes, now are used to alleviate flooding and to provide water for water-based recreation, for water quality improvement and for hydroelectric power production. Together, their storage capacity is 3.2 million m^3 a significant proportion of the total 13.9 million m^3 of storage available in the basin.

By a federal act[2] dated May 12, 1870, the federal Department of Public Works was placed in exclusive control of the navigation of the river and of all works constructed, including those for hydroelectric power. At the time the three Public Works' reservoirs (Temiskaming, Quinze and Kipawa)

1 Sessional paper No. 19, 1912

2 An Act respecting certain Works on the Ottawa River, May 12, 1870

were built, the only hydro power plants in operation on the Ottawa was the Chaudière development. Ontario and Quebec to this day share the power output there. The second hydro power site to be developed on the river was at Chats Falls in 1931-32, where the two separate but identical stations share the power between Quebec and Ontario.

It was in January 1943 that an agreement was reached between Quebec[3] and Ontario[4] regarding the division of the remaining water powers of the interprovincial reach of the Ottawa. Ontario, in the 1943 Agreement, was granted Cave and Fourneaux (now called Otto Holden), Des Joachims and Chenaux, plus the rights to one-half of Paquette Rapids (still undeveloped). Quebec was granted the Rocher Fendu, Carillon and one half of Paquette Rapids.

Most of the more than forty hydroelectric power plants in the Ottawa River basin were built in the period from 1920 through 1960. The largest Ontario stations are the Ontario Hydro stations at Des Joachims, Otto Holden and Chenaux, all built in the post World War II period. For Quebec, the largest station in the basin, Carillon, was built by Hydro Quebec in the early 1960's. These four stations were built as a result of the 1943 power-sharing agreement.

Considerable power development has also taken place on the larger tributaries, viz., the Gatineau, Lièvre in Quebec and the Madawaska and Montreal in Ontario. In order to increase hydroelectric energy production, several additional large upstream reservoirs were built.

A listing of principal reservoirs and their characteristics is attached. The 13,9 million m^3 of available storage represents less than one-half of the average annual spring runoff. Any further increase in the quantity of available storage by the creation of additional reservoirs would not

3 An Act respecting the water power of the Ottawa River

4 The Ottawa River Water Power Act, 1943, (Ontario).

only reduce flood damages downstream but would also increase winter production of hydroelectric energy, with no increase in installation.

Evolution of the Present Regulating Committee

Up until the end of World War II, the needs of the few hydroelectric developments on the river were adequately met by the simple operating procedures carried out since 1915 at the Quinze and Temiskaming reservoir dams for navigation and flood mitigation. In 1933 the federal responsibility for obtaining hydrological and meteorological data on the river was transferred from the Department of Public Works to the Water Resources Branch of the Department of Northern Affairs and National Resources. Similar data was being obtained on the Quebec tributaries by the Quebec Streams Commission and the Gatineau Power Company (now Hydro-Quebec) and on the Ontario tributaries by the Ontario Hydro Electric Power Commission.

The considerable development that took place in the post war years resulted in a significant change in the regime of the river and in the demands for its uses. The simple operating procedures of the past were no longer workable. Also, the need for a detailed study of the river basin became apparent. In 1949, by Order-in-Council PC 228/283 dated January 22, authority was granted to the Department of Public Works to engage a consulting engineer (Mr. S.S. Scovil) to act as Water Controller for the Department and to compile and consolidate the hydrological and meteorological records of the various agencies. At the same time, Mr. Scovil was similarly engaged by Ontario Hydro and by Gatineau Power. When Mr. Scovil died in 1954 the Department of Public Works did not engage another consultant; however, the two hydro agencies engaged Mr. J. Woodside of the Gatineau Power Company as their representative to make recommendations to the Department on the operation of all the reservoirs above Temiskaming.

Conflicting interests of hydro generation versus logging and boating still continued and led to the Department calling a meeting of all interested parties in April 1955 to resolve the difficulties being encountered by excessive and frequent fluctuations of levels and flows in the reaches of the river below Temiskaming. This meeting resulted in the 1955 draft of the first proposed control of the waters of the Ottawa River. At that time, the Temiskaming dam was considered to be the main control point on the river and the reasoning behind the Public Works proposal was that if precise regulation rules could be adopted for Temiskaming, the operation of the hydro reservoirs and generating stations above and below Temiskaming could be coordinated to it. Without affecting the independence of the hydro agencies, it was believed this would result in more efficient planning, while at the same time being more compatible with the navigation and flood mitigation requirements. There was an improvement; however, due to the lack of documented physiographical and streamflow knowledge of the entire basin it was only partially successful.

In 1957, the federal government initiated negotiations with the Provinces of Quebec and Ontario for the establishment of an engineering board to study the entire Ottawa River basin. The Water Resources Branch undertook to compile the storage and streamflow records from the various government and private agencies and to prepare a description of each of the sub-basins in the watershed. The gathering of this material into a single publication where it would be readily available was seen as a necessary preliminary step for the intended study. The material has been published in three separate appendices to the 1962 Report entitled "Hydrological Investigations of the Ottawa River." The availability of this material made it possible for each of the users of the river to better understand the river as a whole and to better recognize the needs of other users. More importantly, it led to improved regulation.

In 1956 when Mr. Woodside retired, Ontario Hydro and Hydro Quebec each nominated a representative and an alternate to look after their respective interests. Thus the initial Ottawa River Regulation Committee was formed. The Committee had no financial budget. Each agency was responsible for all salaries, time, travel and other expenses for its representatives. The Ottawa River Regulation Committee was ad hoc and had no official mandate.

Also in 1965 the Ottawa River Engineering Board's Report on Hydrology and Regulation of the Ottawa River, with its two appendices became available. This report, along with the earlier 1962 report by the Water Resources Branch, was used extensively by the ad hoc committee and is still a valuable reference.

Since 1965 the regulation and forecasting methods outlined in the Ottawa River Engineering Board's report and Appendices have been employed, although success had been limited.

By 1970, with the more liberal use of long distance and conference telephone calls and the greater number of recording stations being used, the daily data from all of the many points in the watershed were being obtained and assembled by 11.a.m. each day.

Up to 1975 the operating procedures were basically unchanged from those outlined in the 1955 Draft of Proposed Control of the Waters of the Ottawa River. While the procedures were applicable to only the Quinze and Temiskaming reservoirs, they were interdependent with the operation of all of the Ottawa River basin generating stations and reservoirs owned by the hydro agencies.

Following the spring flooding on the lower Ottawa River in 1974, and in particular in the Montreal area, representations were made by the Province of Quebec for the formation of a Federal-Provincial committee to study the feasibility of reducing the annual spring flooding and augmenting the late summer low flows. The committee which was formed was called the Committee on Flow Regulation, Montreal Region, and established 12 sub-committees, each with a specific task. On the Federal side, there were 4 departments involved, MOT, DIANA, EC and PWC, with Environment Canada playing the lead role under their responsibilities of the Canada Water Act. On the Quebec Provincial side was the Ministry of Natural Resources responsible for flooding matters and Hydro-Quebec. From the Ontario side, there was representation from the Ontario Ministry of Natural Resources and a representative from Ontario Hydro was on some of the sub-committees.

A copy of the report dated 1976 is available in most Government Libraries.

In February 1977, the Ottawa River Regulation Planning Committe was similarly formulated to carry out further studies and to implement the recommendations made by the Committee on Flow Regulations. The participating government departments and agencies were as follows:

Canada - Fisheries and Environment (now Environment only)
- Transport
- Public Works

Quebec - Natural Resources changed to Environment
- Hydro Quebec

Ontario - Natural Resources
- Ontario Hydro

Four sub-committees, each with specific terms of reference, were established as follows:

Sub-committee 1 - Regulation Planning Committee, with two working groups

Sub-committee 2 - Flow Forecasting Committee with a working group

Sub-committee 3 - Flood Warning Committee

Sub-committee 4 - Permanent Committee

Under Sub-committee 1, a sophisticated optimization computer reservoir management model was developed having three time frames as follows:

Long term - 52 weeks for annual planning

Mid term - 14 weeks to span the spring freshet period for reservoir filling and early flood warning indication

Short term - 10 days for daily reservoir operation routing and flood warning.

This optimization model is called ORRMS, Ottawa River Regulation Modelling System, and is more commonly referred to by the French version as MORRO. By using a range of coefficients to weight the degree of flood protection provided, the loss or gain in power production necessary to produce a certain gain or loss in flood control benefit can be evaluated. Thus, at any point in time, the decision makers are able to evaluate alternative courses of action in the integrated management of the reservoirs. The model was developed by a working group with the help of an outside consultant. All departments and agencies contributed towards the cost with Environment Canada paying a much major amount.

This model is operated by Environment Canada using the Data Crown computer and with the most probable natural runoff forecast input being supplied by Hydro Quebec model.

Under Sub-committee 2, a forecast/routing computer model was developed based on the U.S. Army Corps of Engineers SSARR model (Streamflow Synthesis and Reservoir Regulations). With this model the Ottawa River watershed was divided up into several (initially 50 plus) sub-basins. Each sub-basin could be an entire tributary, part of one, or an area between two measuring points either on a tributary or on the main stem. The geographical and hydrological characteristics of each sub-basin was classified, calibrated and codified such that when temperature and precipitation forecasts were entered, the model would determine the natural run-off from each sub-basin on a 10 day running daily basis. A routing feature was added such that the individual run-offs from each sub-basin with time travel lags could be accumulated to produce a 10 day forecast at all measuring points or control points on the river. The end product is a daily printout of run-off, run-off rate, inflow, elevation and outflow (with % full in the case of a reservoir) for day -1, day 0, day plus 1 to day plus 10 for the 40 odd sub-basins and for all of the major stations in the watershed.

The Canada-Quebec-Ontario Agreement Respecting Ottawa River Basin Regulation was signed on March 2, 1983 and established the permanent committee consisting of the following:

Principal Reservoirs in the Ottawa River Basin
(having live storage in excess of 200 million m3)

River	Reservoir	Capacity Millions m3	Operating Range m	Control Owner	Control Operator	Original Purpose of Reservoir
Ottawa	Dozois	1,863	9.14	HQ	HQ	Hydro power
	Rapid VII	371	1.83	HQ	HQ	Hydro power
	Quinze	1,308	3.40	DPW	DPW	Navigation
	Timiskaming	1,217	4.00	DPW	DPW	Navigation
	Des Joachims	229	3.00	OH	OH	Navigation
Montreal	Lady Evelyn	308	4.50	OH	OH	Hydro power
Kipawa	Kipawa	673	2.60	DPW	HQ	Navigation, Hydro power
Madawaska	Bark Lake	374	9.50	OH	OH	Hydro power
Gatineau	Cabonga	1,565	4.72	EQ	HQ	Hydro power
	Baskatong	2,649	15.55	EQ	HQ	Hydro power
Lievre	Mitchinamecus	554	13.00	EQ	EQ	Hydro power
	Kiamika	379	12.00	EQ	EQ	Hydro power
	Poisson Blanc	625	9.70	EQ	EQ	Hydro power

HQ - Hydro-Quebec
OH - Ontario Hydro
EQ - Environment Quebec
DPW - Department of Public Works

Ottawa River Regulation Planning Board - having representation from the Federal Departments of Environment, Transport and Public Works; from the Province of Quebec by Quebec Environment and Hydro Quebec and from the Province of Ontario by Ontario Natural Resources and Ontario Hydro.

Ottawa River Regulating Committee - having representation by those agencies and departments having control dams. These include Environment Quebec, Hydro Quebec, Ontario Hydro and Public Works.

Ottawa River Regulation Secretariat - consisting of an executive engineer and one or more regular employees plus, when necessary on a part time basis, a number of seconded employees from the participating departments or agencies.

The Secretariat would be the working arm for both the Board and the Committee. Its annual cost is currently estimated at $500,000 for salaries, computer time, public relations, special studies and office supplies. The federal government (DOE) will be responsible for one-half of these costs and each province responsible for one-quarter.

PROBABILITY FORECASTS OF WATER LEVELS AND OUTFLOWS OF THE GREAT LAKES

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PROBABILITY FORECASTS OF WATER LEVELS AND OUTFLOWS OF THE GREAT LAKES

The Water Planning and Management Branch, Inland Waters Directorate, Ontario Region of Environment Canada, through its Great Lakes St. Lawrence Study Office, provides technical support for the study and management of the Great Lakes. This office supports, by membership and technical advice, two of the Boards which execute the Orders of the International Joint Commission governing the regulation of the water levels and outflows from Lake Superior and Lake Ontario. As part of this technical support, it provides forecasts of water levels and outflows from these lakes for use in the decision making process of these Boards. These decisions are for purposes of reservoir operation to meet the requirements of the Orders of the International Joint Commission. In addition, forecasts of Great Lakes water levels are prepared monthly as an outlook for the next six months. These forecasts are distributed to the general public in the "Monthly Water Levels Bulletin - Great Lakes and Montreal Harbour". All of these forecasts are internationally coordinated. This paper will briefly describe the basic methodology behind these forecasts of water level and outflow.

Because the reservoir time lags on the natural reservoirs vary from about 32 months for Lakes Michigan-Huron to about 5 months for Lake Erie together with the fact that the outflows from Lake Superior are regulated on a monthly basis, the forecast method has been developed using a basic time period of one month. The basic model is a reservoir routing model which routs water supplies through the Great Lakes System. For Lakes Superior and Ontario the regulation plan currently in effect is used. Lakes Michigan-Huron which are considered as a single reservoir, and Lake Erie both have uncontrolled outlets and act through their range of water level fluctuations as natural linear reservoirs. The basis

of routing water supplies of various probabilities through Lakes Michigan-Huron, St. Clair and Erie is described in Appendix B, Lake Regulation, of the International Great Lakes Levels Board Report to the International Joint Commission[1]. The method of routing the effects of the levels of the upstream lakes on the water supplies to Lake Ontario is described in (2). Since long term (several months) forecasts of meteorological variables are not available, a single valued forecast of future water level or flow is certain to be in error. However, by routing of various probabilities of water supply sequences, a range of probable water levels or flows can be produced.

The basic data used in producing the monthly forecasts of levels and flows of the Great Lakes are the lake levels themselves together with the probability of the net basin supplies to each of the lakes. Since the forecasts are made at the beginning of each month, the current lake levels are computed from daily water levels determined from gauging patterns which have been developed internationally. Great Lakes water levels in Canada are obtained from the water levels data base which is maintained by the Marine Environmental Data Service (MEDS) operated by Ocean Science and Surveys of Fisheries and Oceans Canada. This data base is maintained in the Energy, Mines and Resources Canada Cyber 74 computer in Ottawa. These data are assembled daily from 13 Canadian Data Acquisition Telemetry System (DATS) water level gauges located at Thunder Bay and Michipicoten on Lake Superior, Thessalon and Goderich on Lake Huron, Belle River on Lake St. Clair, Bar Point, Port Stanley and Port Colborne on Lake Erie, Port Weller, Toronto, Cobourg and Kingston on Lake Ontario and Jetty No. 1, Montreal Harbour. These data are generally available by on-line data communications and terminal shortly after 1000 hours Monday to Friday. Similar data

for United States water level gauges on each lake are available daily by telephone from the United States Army Corps of Engineers offices in Detroit and Buffalo. The United States data is assembled through a similar system operated by the United States National Oceanographic and Atmospheric Administration.

A major component of the water supply to each downstream lake is the inflow from the lake upstream. The exception to this is Lake Superior whose total water supply is from its land basin (about 65 percent) and lake surface (about 35 percent). However, as you move downstream in the system, the inflow from the upstream lake becomes increasingly important. The water supply to Lakes Michigan-Huron (considered one lake for hydrologic purposes) is about 50 percent from the land and lake surfaces and about 50 percent as the outflow from Lake Superior. For the downstream lakes, Erie and Ontario, the proportion of their water supply is over 80 percent from the upstream lake.

The forecasting operation starts with the current beginning of month level for each of the Great Lakes. Six month water supply sequences with exceedance probabilities of 5, 50 and 95 percent are routed through the regulation plan for Lake Superior and water levels and outflows for the six month period computed. The exceedance probabilities of the six month supply sequences for all lakes are derived from the historical record of 83 years. In turn, these outflows are combined with the same exceedance probabilities of local supply to Lakes Michigan-Huron and routed through that lake to produce the six month forecast of levels and flows for Lakes Michigan-Huron. The most probable outflows from Lakes Michigan-Huron, combined with the 5, 50 and 95 percent exceedance probabilities of local supply to the downstream lakes, are routed through the St. Clair River,

Lake St. Clair, the Detroit River, Lake Erie and the Niagara River to produce levels and outflows for Lakes St. Clair and Erie. The calculation of the routing through Lake Ontario is weekly for the operational purposes of the International St. Lawrence River Board of Control. However, the data is all published in the Monthly Water Levels Bulletin using the time unit of one month.

A conceptual model based on a regression of the water balance elements of the land areas and water surfaces and the next month's local water supply to the lakes has been developed[3] and is run in parallel to the above described model. The water supplies are routed using the observed end-of-month water levels described previously. The routing model is the same. The basic data is the air temperature, dew-point temperature, percent possible sunshine. Using observed precipitation and Morton's method[4] of estimation of evapotranspiration and mean values where other water balance elements are not available, the water supply is forecast and routed through the reservoirs of the Great Lakes. Error frequency analysis for three years of operation shows that the errors are of similar magnitude and frequency to the routing of water supply probabilities. As a result, arguments for network improvement are difficult to make with such a result.

The Monthly Water Levels Bulletin forecasts and press releases are transmitted to Burlington by telephone and facsimile where graphic masters are prepared by Ocean Science and Surveys for printing by commercial printer. These forecasts are prepared within 5 days of the end of month and distributed by Ocean Science and Surveys of Fisheries and Oceans Canada. About 2,000 copies of this bulletin are distributed monthly.

In summary, the Great Lakes-St. Lawrence Study Office in Cornwall, Ontario, prepares a monthly forecast of Great Lakes water levels. The model used is a reservoir routing model through which various exceedance probability of six month supply sequences are routed to obtain a range of water levels which have various exceedance probabilities. These provide a range of possible occurrences - the 5 percent exceedance probability if wet conditions prevail, a most probable value (50 percent exceedance probability) and the 95 percent exceedance probability should dry conditions occur. These forecasts are widely distributed to interested power utilities, navigation companies, riparians and other users of the Great Lakes.

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RESERVOIR REGULATION SCHEMES FOR FLOOD CONTROL

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SUMMARY

One of the major mandates of the Alberta River Forecast Centre (ARFC) is to advise on reservoir operations in order to provide flood control and optimum management of the water resources of the province. As part of this mandate the ARFC came up emergency flood regulation procedures for several major provincial reservoirs. These procedures were based on the methodology originally developed by the U.S. Corps of Engineers.

This paper briefly outlines the methodology behind these procedures and the operational rules to be followed during a flood situation and presents an example to illustrate the use of such procedures. The methodology presented will enable hydrologists and operation staff to make quick and objective decisions in a given runoff situation.

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RESERVOIR REGULATION SCHEMES FOR FLOOD CONTROL

Thai Nguyen [1] and David Graham [2]

Introduction

Until recently, operation of the provincial reservoirs in Alberta has relied heavily on the familiarity and experience of the operation staff with the projects and the catchment areas. The flood forecast service has been available since 1969 but the forecasts could not be used in quantitative terms for reservoir regulation. Decisions on the releases were made on the basis of the past flood experience and the rate of rise within the reservoir rather than the result of an hydrologic analysis. Sophisticated computer models are available at the headquarters of Alberta Environment but could only be operated by professional hydrologists and a quick decision on the release was not feasible at times.

This paper discusses a methodology that was recently derived and adapted at the Alberta Environment's River Forecast Centre (ARFC) for the development of flood regulation schemes for several major provincial reservoirs. The procedure described hereafter was originally proposed by the US Corps of Engineers as an emergency regulation scheme. The concept was then further extended at the ARFC to incorporate the flood forecast parameters and meant to be used as a guide for the operation staff to make quick decisions on the required release in the consultation with the forecasting staff.

Regulation Scheme Formulation:

The original concept proposed by the US Corps of Engineers is meant to be used only in emergency situations such as communication line failure during an active flood period. During such a period the only information available to the operation staff is the rate of rise of the water level in the reservoir and probably the public weather forecasts. In these circumstances, the operation of the dam must be as conservative as it is practical, to avoid unnecessary high release, and assure the structural safety of the dam.

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The original concept developed suggests that an assumption can be made that permits a prediction of the minimum inflow volume that can be expected from the flood. This volume can be obtained by assuming the inflow has reached the maximum value at the dam site at the time of the observation and a volume of inflow can be calculated by integrating the area below the recession curve selected for the hydrograph (figure 1). Having calculated the minimum expected inflow volume to the project, the minimum release could be computed simply by balancing the remaining storage space in the reservoir and the expected inflow volume.

By monitoring the change in storage and the release, current inflow could then be calculated and the minimum expected flood volume could be approximated (Figure 1). The minimum required release then can be determined by balancing the remaining storage space and the runoff volume expected as the flood progresses.

The U.S. Army Corps of Engineers has suggested that the minimum required released can be calculated by solving the following equation:

$$S_A = \alpha\ T_S\ (Q_C - Q_R[1 + \text{Log}_e\ (Q_C\ /Q_R]) \qquad (1)$$

where:

S_A = remaining storage space in reservoir ($1000m^3$)
α = 3.60 (unit conversion factor)
T_S = basin time of storage hours
Q_C = current inflow to reservoir (m^3/sec)
Q_R = minimum required release (m^3/sec)

Further information on the development of the equation (1) could be obtained from references (1) and (2).

A regulation schedule similar to figure 3 can then be prepared for projects with gated spillways. It is worth noting that this schedule is only applicable in "without forecast" situations and should be used only in emergency situations where the flood forecast service is unavailable or where there is communication failure between the forecast office and the dam site.

The concept represented in the equation (1) was further extended at the ARFC to incorporate the flood forecast information. Assuming that the flood can be predicted T_W in advance (Figure 2), if the intended release is Q_R, the flood runoff to be stored below the assumed recession curve can be approximated using the equation (1) as

$$S_2 = \alpha\ T_S\ [Q_P - Q_R(1 + \text{Log}_e\ Q_P/Q_R)]$$

The net floodwater volume to be stored during the rising limb of the hydrograph can be approximated as

$$S_1 = \alpha\ T_W[(Q_C + Q_P)/2 - Q_R]$$

The equation (1) then can be rewritten for the situations with flood forecast as follows:

$$S_A = \alpha\ T_W\ [Q_C + Q_P)/2 - Q_R)] + \alpha\ T_S\ [Q_P - Q_R\ (1 + \text{Log}_e\ Q_P/Q_R)] \qquad (2)$$

where:

S_A = remaining storage space for floodwaters (1000 m^3)
α = 3.60 (unit conversion factor)
T_W = warning time (hours)
T_S = basin time of storage (hours)
Q_C = current inflow to reservoir (m^3/sec)
Q_R = minimum required release (m^3/sec)
Q_P = predicted peak flow (m^3/sec)

Equation (2) enables hydrologists to determine minimum discharge required from the dam given remaining storage space, predicted peak flow, times to peak and current inflow. Solutions to the equation (2) can be presented in graphical form for different predicted peak flows and times to peak and examples of such graphs are shown in figures 4-7.

Application of the Proposed Schemes:

The methodology represented by equations (1) and (2) was recently adapted for several major multi-purpose reservoirs in the province of Alberta. Few additional rules were however used together with those formulas to improve the efficiency of the operation and to assure the safety of the dams and their operations.

At the Alberta River Forecast Centre, the flood regulation procedure using flood forecast information can be summarized as follows:

1. Maintain the reservoir level at or below seasonal levels if there is high runoff potential from the upstream area such as in prolonged wet period situations or prior to a predicted above normal mountain snowmelt peak flow.

2. As soon as the flood forecast is received at the reservoir operation office, the required release must be determined by the reservoir manager based on the predicted peak flow, current flow and available storage space (using the charts similar to Figures 4-7). Keep in mind that these are minimum releases suggested based on current available storage space and the streamflow forecasts, and the reservoir operation staff may decide to release higher than the suggested values prior to the active flood period. Higher releases are normally suggested when the weather forecast calls for additional rainfall or snowmelt.

3. In a moderate flood situation, releases from the reservoir should be based on the value suggested by the procedure. If the current release is higher than the suggested value, maintain the current release until the forecast is updated. In the cases where the current release is lower than the suggested value, gradually increase the release to the required level or slightly higher.

   It is important that the release be increased gradually, as sudden changes could create unpredictable problems downstream. A higher increase rate may be acceptable in a severe flood situation to provide better flood control, but should be done with caution.

4. In a severe flood situation, high releases can be made in order to lower the reservoir level in the early stage of the flood. In such a situation, the reservoir releases should be maintained at a level to assure that the combined flow does not exceed the flood stage at downstream locations until the outflow determination procedure (using figure 4-7) suggests that higher flows are required. It has been a traditional practice <u>not to cut down the release while the pool level is still rising.</u> In extremely high local flow situations the release may be reduced temporarily during the peaking period of the local flows to optimize the flood control (this should only be done when there is still large flood space available in the reservoir).

5. Adjust the spillway gates frequently to ensure the required release is met. Update the release as soon as a new forecast is obtained.

6. Reservoir level must not be allowed to exceed the top of Flood Control Pool Level until the spillway gates are fully opened.
7. When the inflow rate drops below the current outflow level, reservoir level will start to fall. The fall of the reservoir level will result in a lower release rate. Adjustment of the spillway gate openings during the drawdown period should not be required until the target level is reached. This is because it is necessary to empty the flood storage space before another flood may materialize. In certain situations, the reservoir operation staff may choose to close the gates gradually during the falling period of the reservoir level. Figure 3 can be used to compute the minimum required release in this period. The target release must be the higher of the current release and the minimum required release.
8. If the flood forecast indicates the critical period has passed, bring the reservoir back to the target level and resume normal operation.

Communication between the River Forecast office and the reservoir operation staff may fail during a flood situation. Should such a situation occur, the reservoir operation staff would have to regulate the project with very limited information on current and future runoff. In the worst case, the only information available to the operation staff would be the current reservoir level and the rate of rise in the reservoir. An estimate of current inflow to the reservoir could still be computed based on the current rate of rise, current release and reservoir characteristics. The inflow estimate could then be used to formulate the release scheme. This would help to improve the situation somewhat until a communication line could be re-established between the operation staff and the River Forecast Office.

The flood regulation procedure in the absence of the runoff forecast service is proposed as follows:

1. Maintain the reservoir at or below the seasonal level if there is potential of high runoff from the area such as in a prolonged wet period situation or prior to the mountain snowmelt peak flow.

2. During the early period of the flood, maintain the reservoir at the current level by passing the inflow, as long as this release plus local flow is not anticipated to exceed the flood stage at downstream locations. Flood storage in the reservoir should only begin when the combined flow is anticipated to exceed this level.
3. Use the Flood Regulation Schedule for "without forecast" cases (Figure 3) to determine the minimum release required on the basis of the current inflow to the reservoir. Keep in mind that this is the minimum release suggested for dam safety purposes. In early flood period the reservoir operation staff may decide to release higher flows based on the current weather conditions, weather forecasts and experience with the watershed. A release of higher than the estimated inflow should never be permitted during an active flood period.
4. Gradually increase the release to the required level as determined in step #3. The rate of change in discharge is preferred not to exceed a pre-determined rate. This is to avoid drastic change in river flows which could cause unpredictable effects downstream. In a severe flood situation, a higher rate of change can be permitted, but should be applied with caution.
5. In the absence of communication with the River Forecast office, warning must be provided to downstream communities by all possible means by the Reservoir Manager if the flow is anticipated to exceed the flood stage at downstream locations. Effort should also be made to re-establish the communication with the River Forecast office as soon as possible.
6. The required release must be updated at least every three hours or shorter.
7. Top of Flood Control Pool Level must not be allowed to be exceeded until the spillway capacity is fully used to discharge the floodwaters.
8. When the inflow drops below the current release, reservoir level will begin the fall. Usually, the outflow from the reservoir will decrease as the reservoir level falls. Adjustment of the spillway gate openings during the drawdown period should not be required

until the reservoir target level is reached. This is because the flood storage space should be emptied as soon as practical before a second flood peak may materialize. In certain situations, the reservoir operation staff may choose to close the gates gradually during the falling period of the reservoir level. Figure 3 could be used to calculate the minimum required release in this period. The target release should be the higher of the current release and the minimum required release.

9. Resume normal operation after the flood.

ST. MARY RESERVOIR EXAMPLE:

The regulation scheme developed for the St. Mary Reservoir is used in this paper to illustrate the applicability of the proposed methodologies to a multi-purpose project.

St. Mary Reservoir is one of four main irrigation reservoirs in the St. Mary - Waterton Irrigation System in Southern Alberta.

Some of the reservoir characteristics are listed as follows:

- F.S.L. elevation 1103.40 m (3620 ft)
- Effective storage 370 x $10^6 m^3$ (299,000 ac-ft)
- Spillway crest elevation 1098.12 m (3602.74 ft)
- Maximum spillway capacity at F.S.L. 1530 m^3/s (54,000 cfs)
- Top of Flood Control Pool F.S.L.

The primary objective of the St. Mary reservoir is conserving water for irrigation use. Flood runoff normally occurs between late May and July but it is desirable that the reservoir be filled before mid July to ensure sufficient water for irrigation use in August and September. Early filling of the reservoir will guarantee the water supply, but of course the flood control potential of the project will be reduced accordingly. Discussion of the seasonal filling scheme for the project is beyond the scope of this paper and will not be included here. Flood forecasts can be generated for the project approximately 24 hours before the flood peak and can be updated every 6 hours. As it is essential to fill the project prior to August 1st every year, it is more difficult to control the flood should it occur late in the runoff season.

Equations (1) was used to derive the graph shown in figure 3 for "without forecast" situations. Equation (2) was then used to develop a series of graphs for different predicted flood peaks and times to peak similar to those shown in figures 4-7. Several historical floods and the 100 year flood were then tested using the proposed schemes for "with" and "without forecast" situations. The results of the test are presented in Figures 8-10.

Following are the points that are worthy of note:

- The proposed schemes can provide even better flood regulation as the floods could have been controlled more timely and the storage space could have been used more efficiently (Figure 8-9).
- The benefit of flood forecasts could have been insignificant in 1975 and 1964 flood regulations as the storage space available prior to the floods was rather large, and as a result early release may not have been critical.
- In a more severe flood situation or in the case of limited storage space available for flood control, the benefit of flood forecasts and regulations based on flood forecasts becomes more apparent. This situation is illustrated in the regulation of the 100 year flood in figure 10.
- The proposed procedures provide a systematic approach to the solution that enables the decisions to be made more quickly to cope with the fast progressing nature of the flood flows. The decision on the release based on the proposed procedures could then be supplemented by the results obtained from a more complete analysis that could only be performed at the headquarters using sophisticated hydrologic models (e.g. SSARR model).
- The availability of such systematic procedures will help inexperienced staff to make the decision adequately and release them from mental pressure in pending for the decisions from the headquarters.

CONCLUSION:

The methodology presented will enable hydrologists and operation staff to make quick and objective decisions in a given runoff situation. A more complete analysis that could take into consideration the predicted flood hydrograph shape, local flows, travel times etc., will provide a better regulation plan. Unfortunately, this type of analysis can only be done by professional hydrologists at the headquarters and could cause some delay on the immediate action plan. At Alberta Environment, it is intended that the proposed procedure be used to make the first estimate on the required release in the flood period. This first estimate will then be evaluated by the river routing package in the SSARR Model (Streamflows Synthesis and Reservoir Regulations). The final plan will then be derived based on the results from such an analysis, and judgements in terms of additional runoff potential or potential damages.

The methodology presented in this paper should only be considered as a general guideline. Some modifications may be required in adapting it for a specific project. The proposed rules which are finally adopted must be used with flexibility by the reservoir managers and operational hydrologists. Fluctuations of the streamflows may not permit the rules to be followed exactly, but indications are that the proposals describe the most probable procedures. Whenever possible, the operational decisions must be made on the basis of consultation from the River Forecast office, especially in the cases of unusually large floods conditions.

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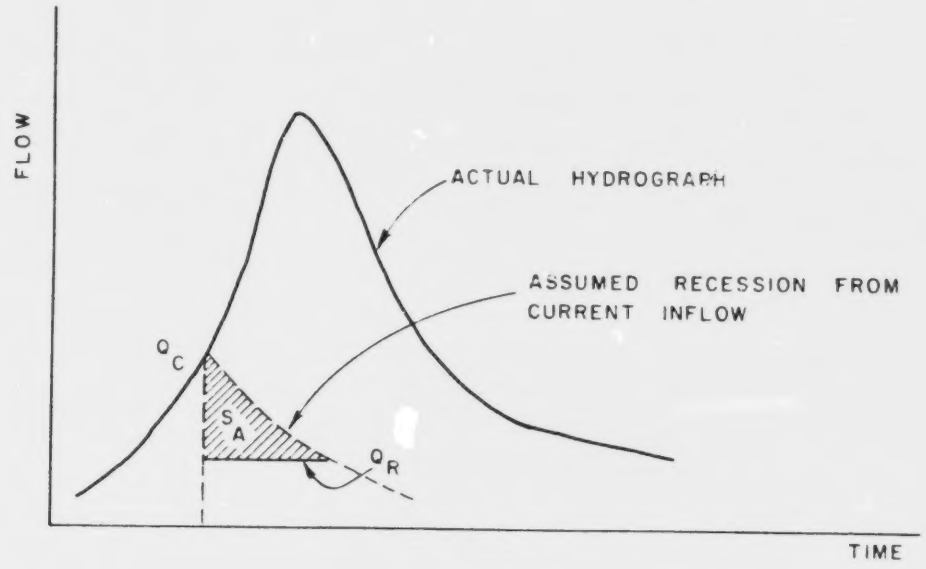


FIG. 1 : APPROXIMATION OF INFLOW VOLUME FROM CURRENT INFLOW.

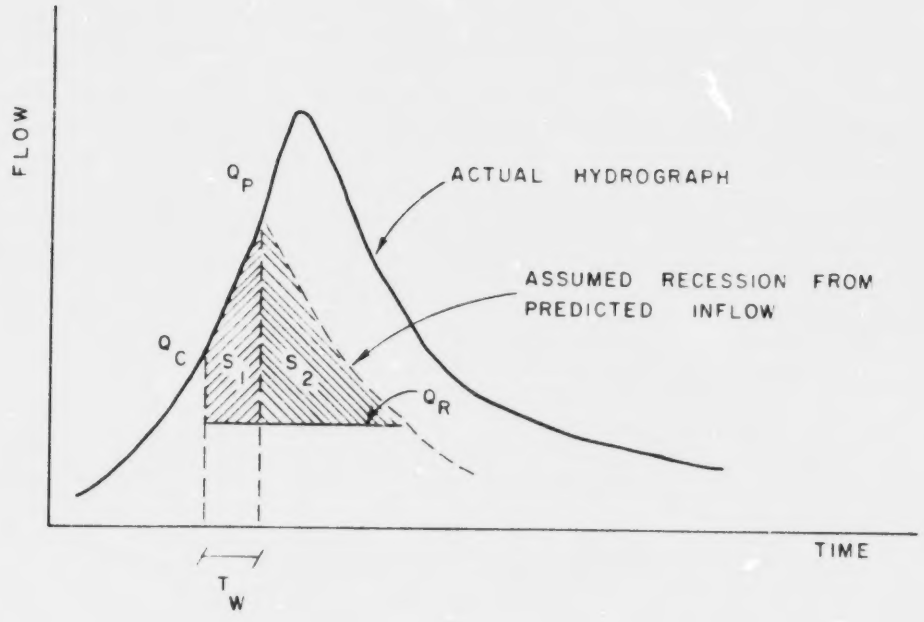
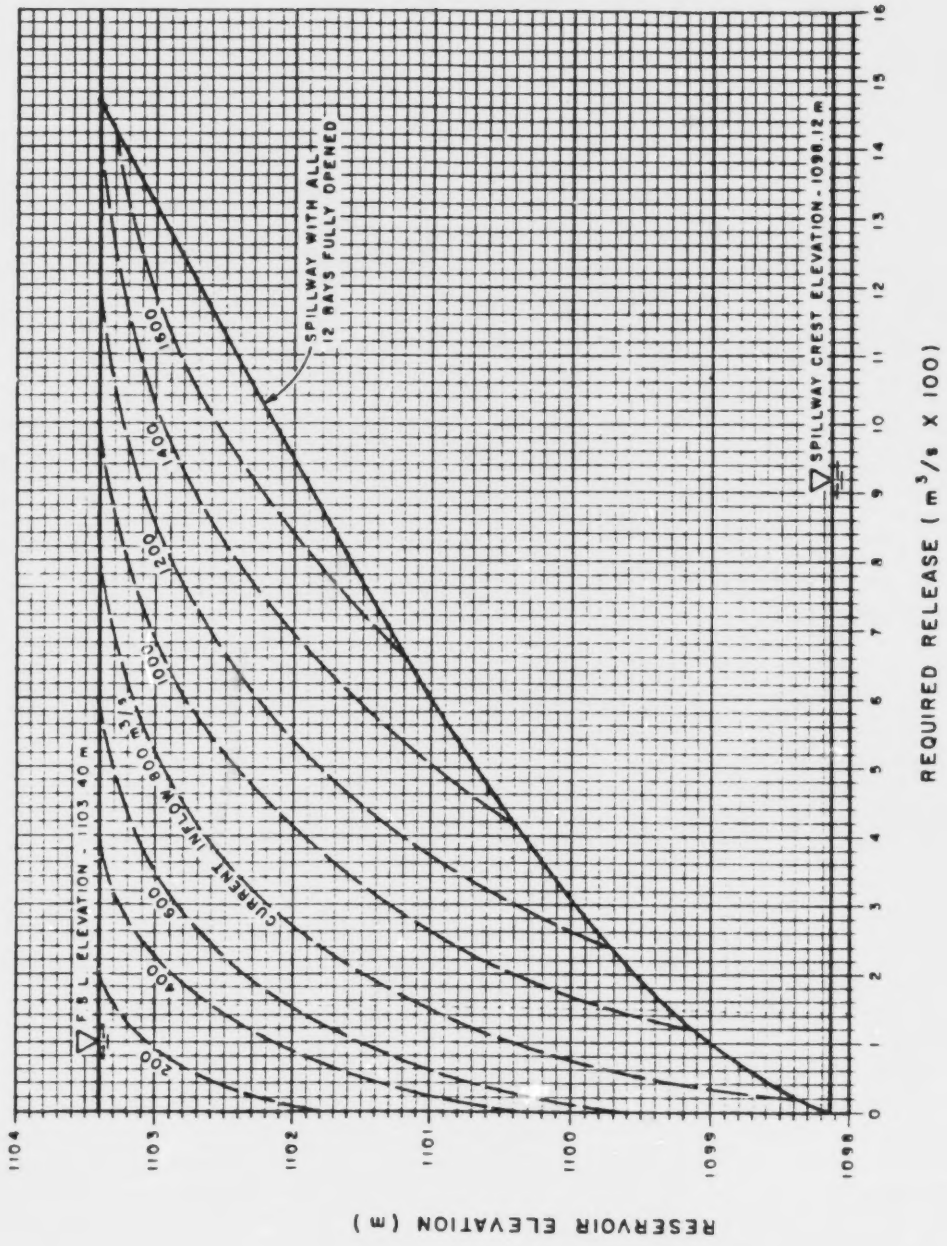
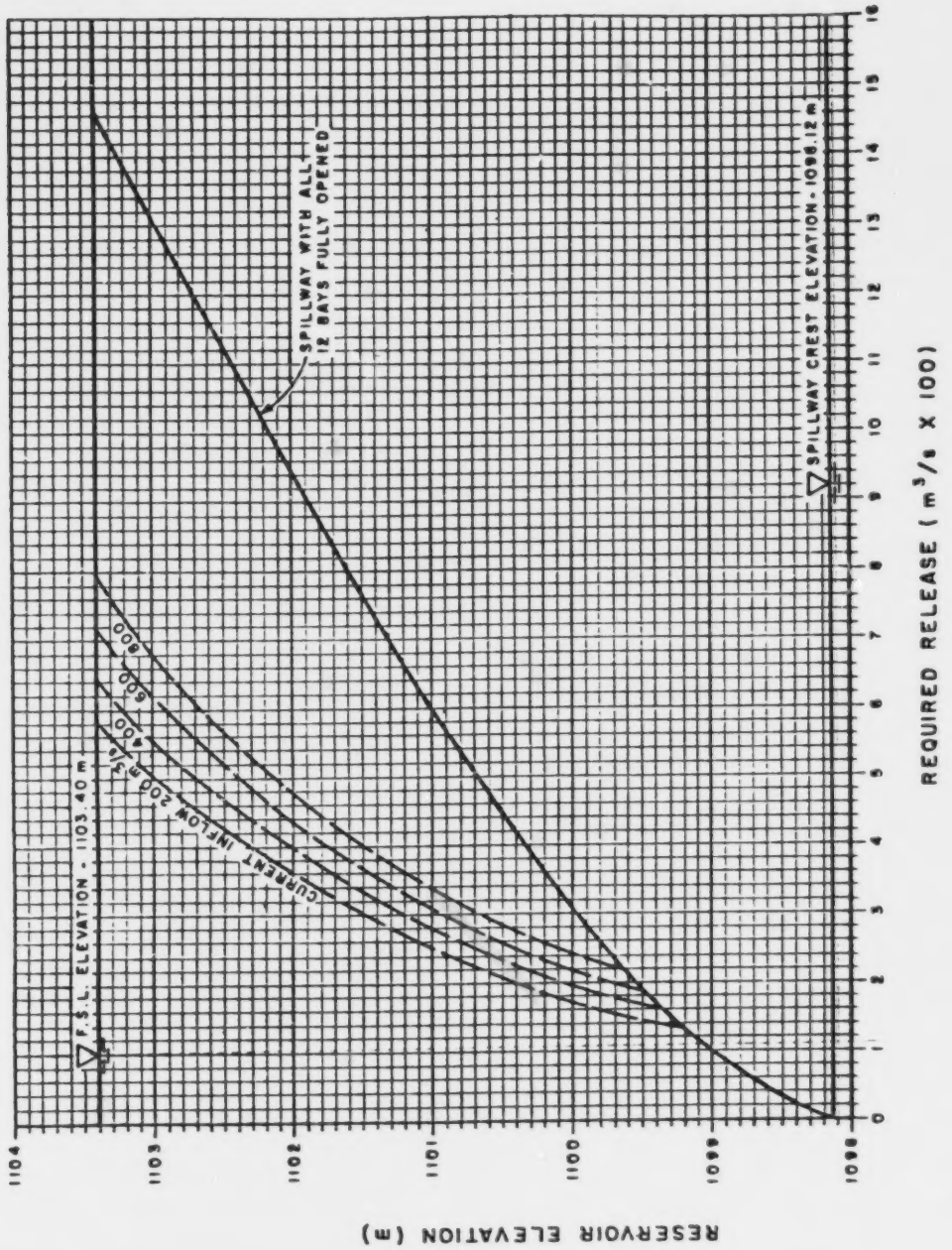


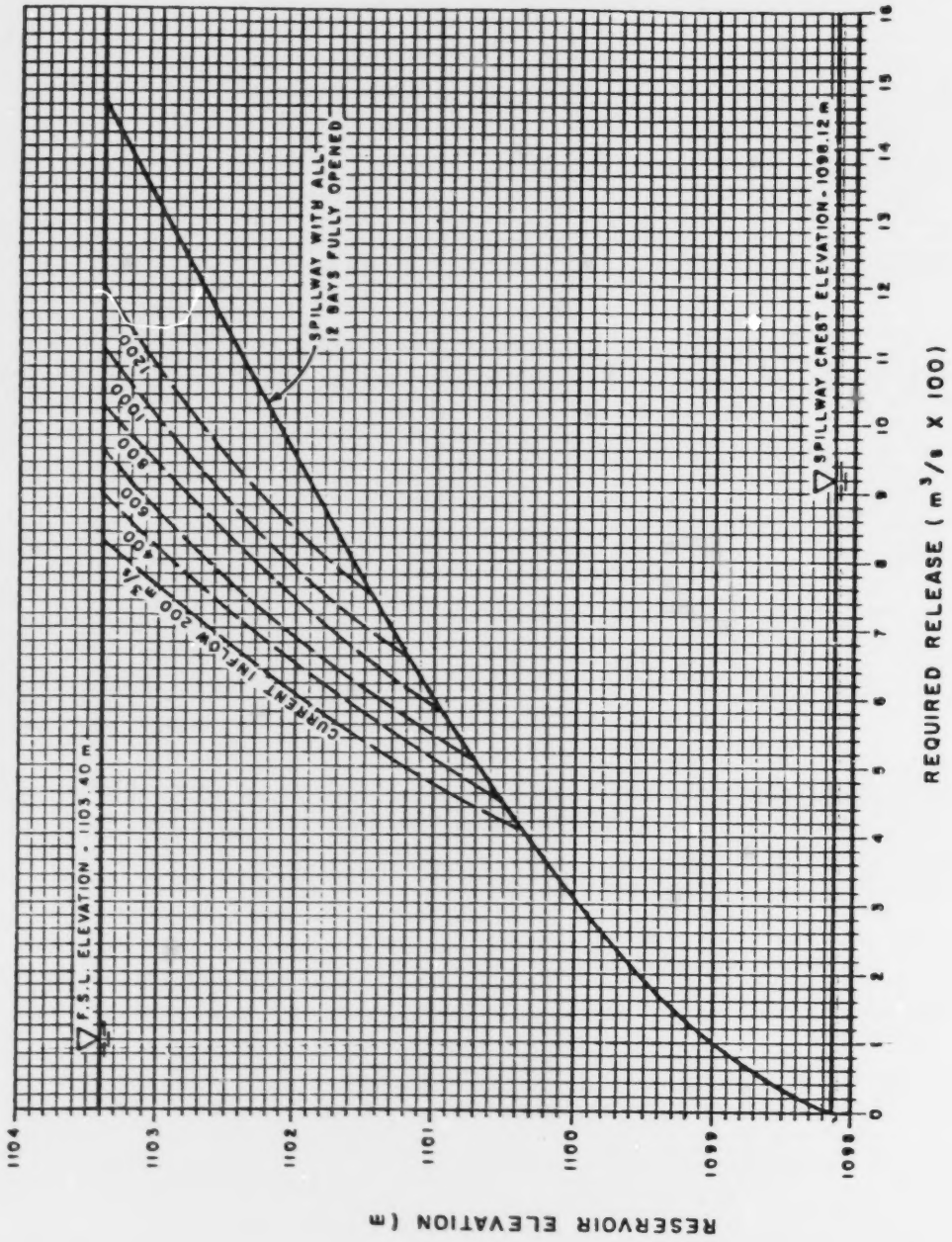
FIG. 2 : APPROXIMATION OF INFLOW VOLUME FROM PREDICTED INFLOW.



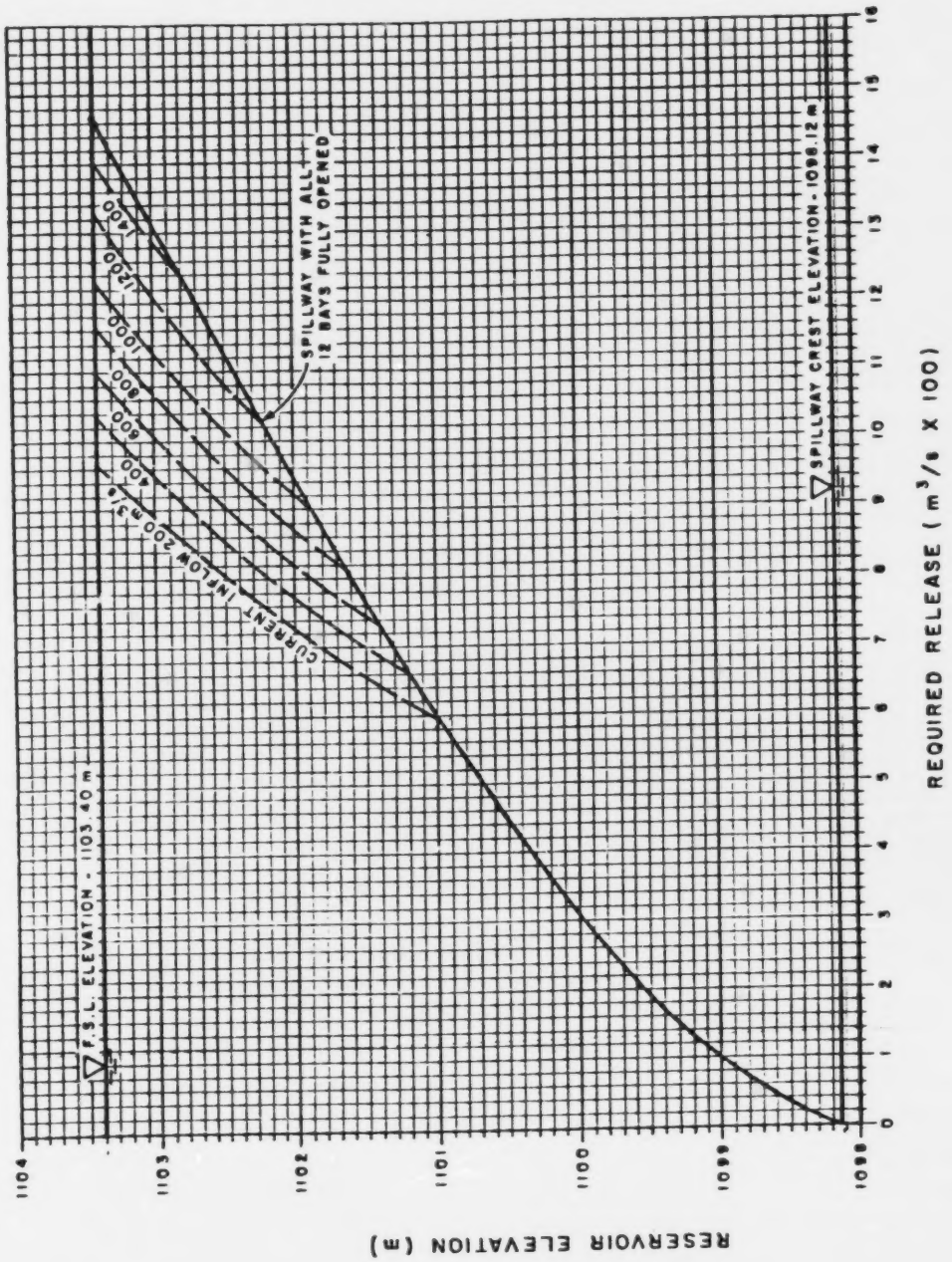
REGULATION SCHEDULE ST. MARY RESERVOIR BASED ON CURRENT INFLOW	
FIGURE 3	METRIC



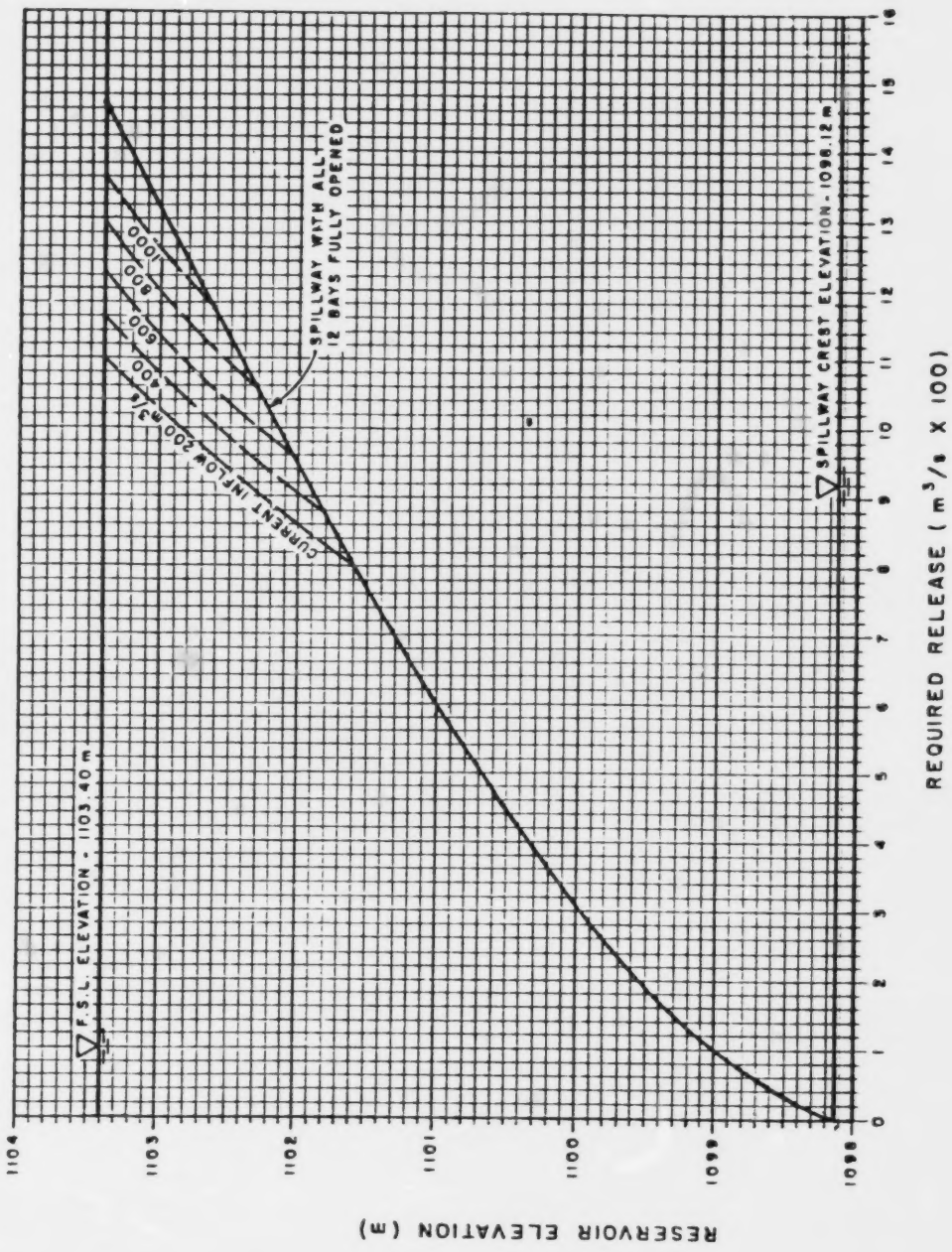
REGULATION SCHEDULE ST. MARY RESERVOIR BASED ON A FORECASTED FLOW OF 800 m^3/s TO OCCUR IN THE NEXT 24 HOURS	
FIGURE 4	METRIC



REGULATION SCHEDULE ST. MARY RESERVOIR BASED ON A FORECASTED FLOW OF 1200 m^3/s TO OCCUR IN THE NEXT 24 HOURS	
FIGURE 5	METRIC



REGULATION SCHEDULE ST. MARY RESERVOIR BASED ON A FORECASTED FLOW OF 1400 m^3/s TO OCCUR IN THE NEXT 24 HOURS	
FIGURE 6	METRIC

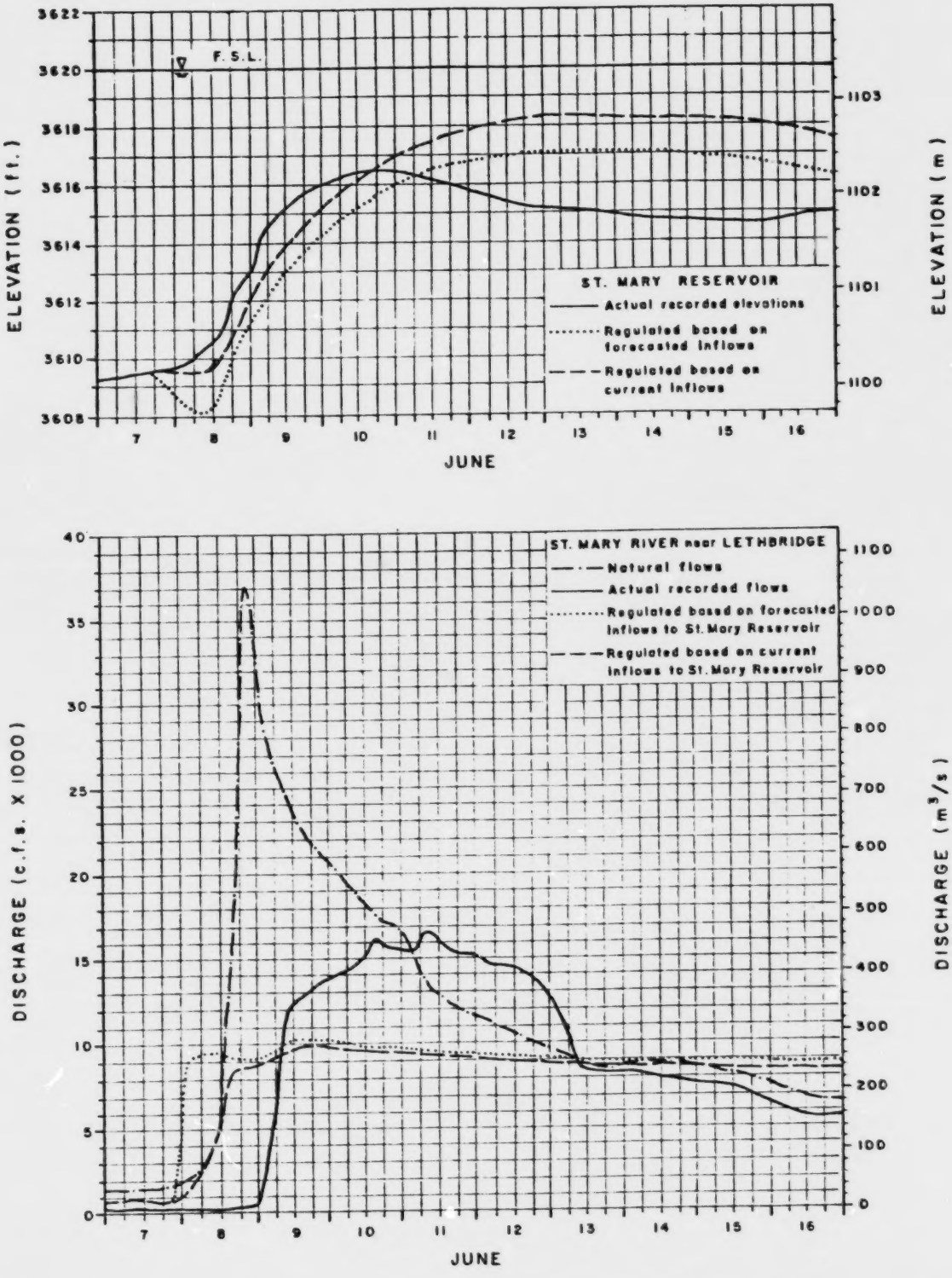


REGULATION SCHEDULE

ST. MARY RESERVOIR

BASED ON A FORECASTED FLOW OF 1600 m^3/s TO OCCUR IN THE NEXT 24 HOURS

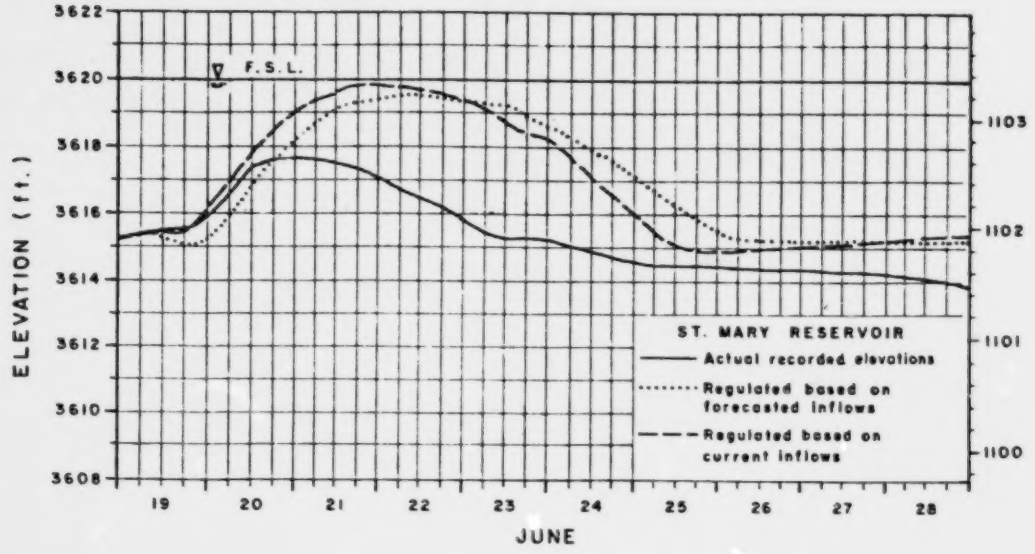
FIGURE 7 METRIC

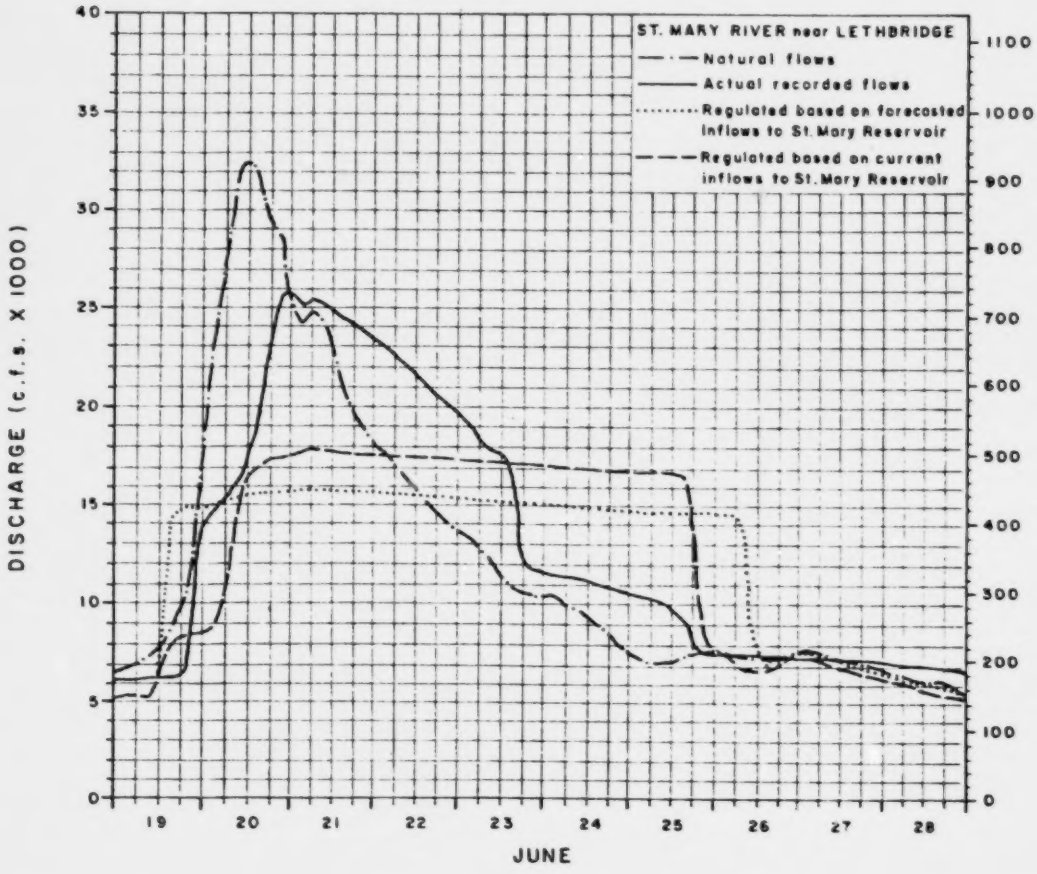


ST. MARY RIVER
NATURAL & REGULATED FLOWS & ELEVATIONS
JUNE 1964 FLOOD

FIGURE 8

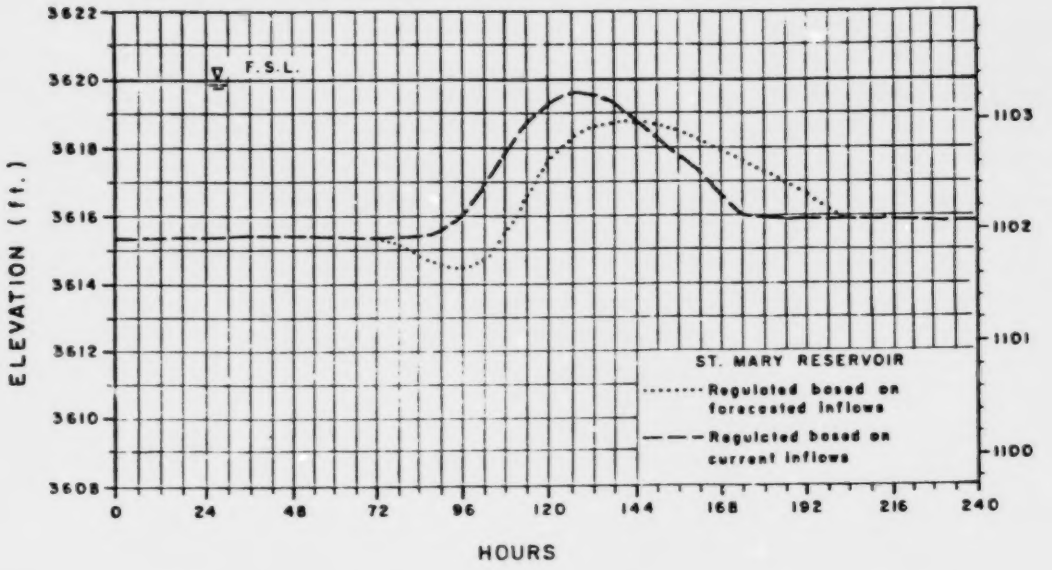
METRIC

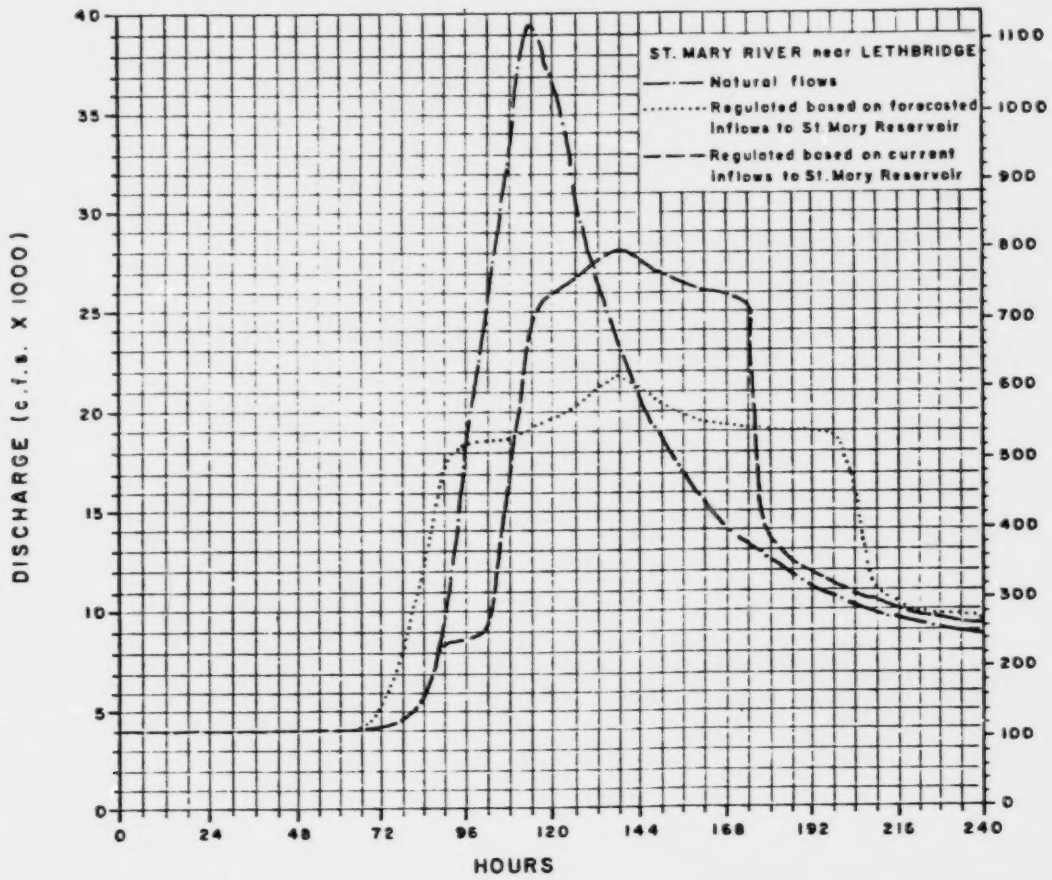




ST. MARY RIVER
NATURAL & REGULATED FLOWS & ELEVATIONS
JUNE 1975 FLOOD

FIGURE 9 METRIC





ST. MARY RIVER
NATURAL & REGULATED FLOWS & ELEVATIONS
1:100 YEAR FLOOD

FIGURE 10

METRIC

DECENTRALIZATION

OF

FORECASTING AND WARNING

FUNCTIONS

NOVEMBER 22, 1983

PETER N. GRYNIEWSKI

I. Introduction

Quantitative water management in Ontario falls under the broad responsibility of the Ministry of Natural resources, Conservation Authorities and Water Management Branch. The Branch works closely with the field arm of the Ministry, Regions and Districts as well as Conservations Authorities. The Authorities were mainly formed to deal with flooding problems and were set up on three principles: watershed basis, provincial-muncipal partnership and local initiative. The 39 Authorities are found in the densely populated 10% of the province. Water management for the remaining 90% is handled by the 8 Regions of the Ministry.

Over the years the province has gradually been turning more responsibility over to the field agencies, the MNR Regions and Conservation Authorities. Decentralization of the streamflow forecasting and warning functions is a case in point. The province desires that the field agencies gain expertise in water management and this becomes one element in the strategy.

II. System Requirements

The following components are considered essential for a viable "Streamflow Forecasting - Warning - Response System":

(a) Data Collection and Management

(b) Streamflow Forecasting

(c) Flood Event Communication

(d) Flood Event Operations

(e) Restoration

A discussion and summary of each component are presented below.

A. Data Collection and Management

Accurate and timely data is the basis of the whole system. Flood predictions are only as reliable as the data they are based on. There are five activities under this component:

(i) Establishment and maintenance of a data monitoring network

(ii) Weather forecasts

(iii) Data Collection/Co-ordination/Transmission

(iv) Data archiving

(v) Training

Extensive observation networks are required to monitor such data as ground conditions, precipitation, temperature, wind, evaporation, radiation, streamflow and the like.

Weather forecasts are a requirement for "early alert" of a potential flood threat and for the management of a flood event.

A centre is required at which all data from monitoring networks is collected, co-ordinated and made available to client groups.

Data archiving includes abstracting, formatting and filing in a manner that allows easy retrieval. It is considered essential for forecasting purposes. Training may be required in various aspects of

instrumentation, data collection methods, archiving and retrieval.

B. Streamflow Forecasting

Forecasting models are the tools for making flood predictions. Development and management of these models are important requirements in the proposed system. Existing manual and computer forecasting models must be assessed. New models should be developed where needed, and all models must be maintained.

Streamflow forecasting involves the interpretation of ground and weather data into runoff (rainfall excess), followed by hydrograph forecasting (flow volumes at a particular time and at a particular point of interest) and stage (flood level) and damage forecasts. The information would allow for effective reservoir operations and decisions on evacuation, removal of goods, sandbagging and other emergency actions.

In summary, this component comprises the following activities:

(i) Development and Management of Models

(ii) Runoff Forecast

(iii) Hydrograph Forecast

(iv) Stage/Damage/Operation Forecast

C. Flood Event Communication

The rapid transfer of data and information

regarding an impending flood event is of utmost importance to the success of the system. It is more critical in Ontario because, in most populated watersheds, the available time for emergency actions prior to the occurrence of a flood peak is relatively short, due to the length of the rivers.

In the past, communication was by telephone and telex. However, present day computer based systems allow for much faster transfer of information.

It is essential to have an early alert to advise agencies with the responsibility of developing streamflow forecasts of impending threats from a weather system.

In turn, these agencies develop flood forecasts and, if there is a significant flood threat, issue flood warnings.

The flood event is monitored, and notices are issued. Notice is also given of the passing of the event.

Component activities include:

(i) Early Alert (Making the field agency aware that an important storm is pending)

(ii) Flood Warning (After a forecast has been made for a flood damage centre, informing the municipality or other appropriate agency of what to expect)

(iii) Flood Event Monitoring and Information Exchange

(iv) Notice of Event Termination

D. Flood Event Operations

During an event, certain operations must be undertaken.

Once a warning is given or a flood is evident, self-help must be employed wherever possible. Families and goods should be removed from threatening flood waters.

Next, contingency plans are put into effect. These commit municipal resources (police, fire, public works and other departments) to carry out operations such as sandbagging, evacuation, ice jam management and the rescue of citizens. If an evacuation takes place, shelter, food and clothing may have to be provided.

During the flood event, flood control structures must be operated. If the threat increases and both local and municipal resources are exhausted, the Minister may declare a provincial emergency where senior government resources through the MNR District assist the municipalities. The Province may call on the federal government for assistance in severe events.

Activities of this component include:

(i) Self-help;

(ii) Municipal Contingency Plans;

(iii) Operation of Flood Control Structures;

(iv) Declaration of Provincial Emergency, with Senior Government assistance.

III. Responsibilities of Parties Within The System

Responsibilities of the parties described in this report are those of a fully developed or "mature" system. The goal of the mature system is to have all parties with highly developed capabilities.

It is recognized that this goal may not be achieved for several years and perhaps, even then, not in total. In some sparsely populated areas with minimal flood problems, only an elementary system is required. In the transition to a mature system, the CAWM Branch will continue to operate under the existing system until the designated agencies of the proposed system develop the required capabilities. Standards for a technical review are to be developed to verify these capabilities. The attached tables outline the proposed responsibilities of the various parties within the mature system.

(a) Synopsis of Responsibilities

(i) Conservation Authorities and Water Management Branch (CAWMB)

The Conservation Authorities and Water Management Branch will be responsible for planning or assisting in conservation authority planning for the establishment of data monitoring networks and a communication system that will rapidly collect and exchange data and information with field agencies. The Branch will coordinate a maintenance and data archiving program.

The CAWM Branch will give an "early alert" of threatening weather systems and forecast the runoff, which may be modified in the field due

to local conditions.

In addition, it will be responsible for setting standards and criteria for various components of the system, recognizing regional differences, developing and maintaining forecast models and preparing the Provincial Flood Emergency Contingency Plan. The Branch will also have an important role in providing consulting services on all aspects of the proposed system to field agencies and training in certain fields. The Branch will coordinate planning of response on a provincial basis and provide self-help information for distribution by field agencies.

(ii) Conservation Authorities or MNR Regions outside of Conservation Authorities.

These groups, in conjunction with the CAWM Branch, will be primarily responsible for the implementation of data networks. In cases where the authority has its own network, maintenance of it will be the authority's responsibility. They will monitor, exchange and ensure the quality of data. Other networks are the responsibility of the individual agency such as Atmospheric Environment Service, Water Survey, and Ministry of the Environment.

Other prime responsibilities include hydrograph prediction, issuing of flood warnings, and the operation of flood control structures. Both agencies will provide consultative services to districts and municipalities for the preparation of Flood Contingency Plans and during the response

process. It is imperative during a flood event that close liaison is maintained between the Conservation Authorities and Regions.

(iii) Municipalities or MNR Districts where no Municipality Exists

The prime responsibilities of these agencies will be the preparation of Flood Contingency Plans, and their implementation during a flood threat. Native communities are assumed to be municipalities, although they are under the jurisdiction of Department of Indian Affairs and Northern Development, Government of Canada, and not under the Province of Ontario.

(iv) Flood Plain Residents

Flood plain residents will carry out self-help wherever possible.

(v) Senior Level of Government

Senior government will be responsible for assessing flood situations and declaring provincial emergencies where local capability has been exhausted. Once a declaration is made, the Provincial Flood Emergency Contingency Plan will be put into effect. Other prime responsibilities include assessment of damages and determination of the need for disaster assistance.

IV. Conclusion

The central agency will concentrate on continuous monitoring and more early recognition and interpretation of

anticipated flood events. From data received from many sources, a runoff forecast will be developed.

The field agencies will be responsible for the hydrograph and stage-damage forecasts. From these they will issue flood warnings to municipalities and other affected parties.

The municipalities are responsible for the protection of their citizens and the reduction of property damage.

Trade-Off Decisions in Streamflow Forecasting for Multiobjective River Basins - The Ottawa River Case

I. Corbu[1], P.C.K. Lau[1]

1.0 INTRODUCTION

Operational decision-making during periods of high runoff, in particular the spring freshet period, represents a complex and challenging problem in the management of large multireservoir, multiobjective river systems. In many cases, such river systems are operated with a view of achieving "satisfactory" levels and/or flows for more than one interest. Such is the situation on the Ottawa River, where for some decision-makers (DMs) the primary objective is to maximize the energy generation and consequently to keep the forebays high and to have full reservoirs at the end of the freshet season. For other DMs, however, the primary objective is to minimize the risk of flooding and consequently to keep the reservoir levels low during the freshet. These two objectives are often conflicting and, consequently, an economical and politically acceptable trade-off methodology is necessary to determine the regulated river flow forecast needed for the operation of the system.

The purpose of this paper is to present the maximum net benefit methodology that allows DMs to identify the "best trade-off" alternative between energy generation and flood-reduction interests in the case of the Ottawa River. This method was proposed by Ontario Hydro to the Ottawa River Regulation Planning Committee (ORRPC) which developed a Runoff Forecasting Model (RFM) and a River Regulation

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(1) Ontario Hydro, Power System Operations Division, Resource Utilization Department.

Model (RRM) to provide guidance for the integrated operation of the reservoirs and hydraulic generating stations located in the Ottawa River Basin (ORRPC, 1980). The method allows water resource managers to automatically compute the "best trade-off" alternative and the corresponding reservoir regulation plan and streamflow forecast over the spring freshet season.

2.0 THE OTTAWA RIVER BASIN

The Ottawa River has a length of 1 160 km and an average annual flow of 1 950 m^3/s at its outlet. The river basin is shown in Figure 1. It has a drainage area of 146 000 km^2, which is larger than the land area of many European countries. The Ottawa River forms part of the boundary between the Canadian Provinces of Ontario and Quebec, and many provincial and federal agencies are involved in, or affected by, its operation. Also, the regulation of this river has international implications since it is a tributary of the St. Lawrence River which drains the Great Lakes and constitutes a natural border between Canada and the United States for part of its length.

Many reservoirs and generating stations have been built over the years to satisfy the increasing need of energy. Now there are 33 major reservoirs with a total live storage of about 14 000 x $10^6 m^3$ and 43 generating stations in the basin with a total installed capacity of about 3 500 MW (shared mainly between Ontario Hydro and Hydro-Quebec).

No reservoirs were built specifically for flood control in the Ottawa River Basin. However, operation of the existing reservoirs for power and navigation has also provided flood control benefits over the

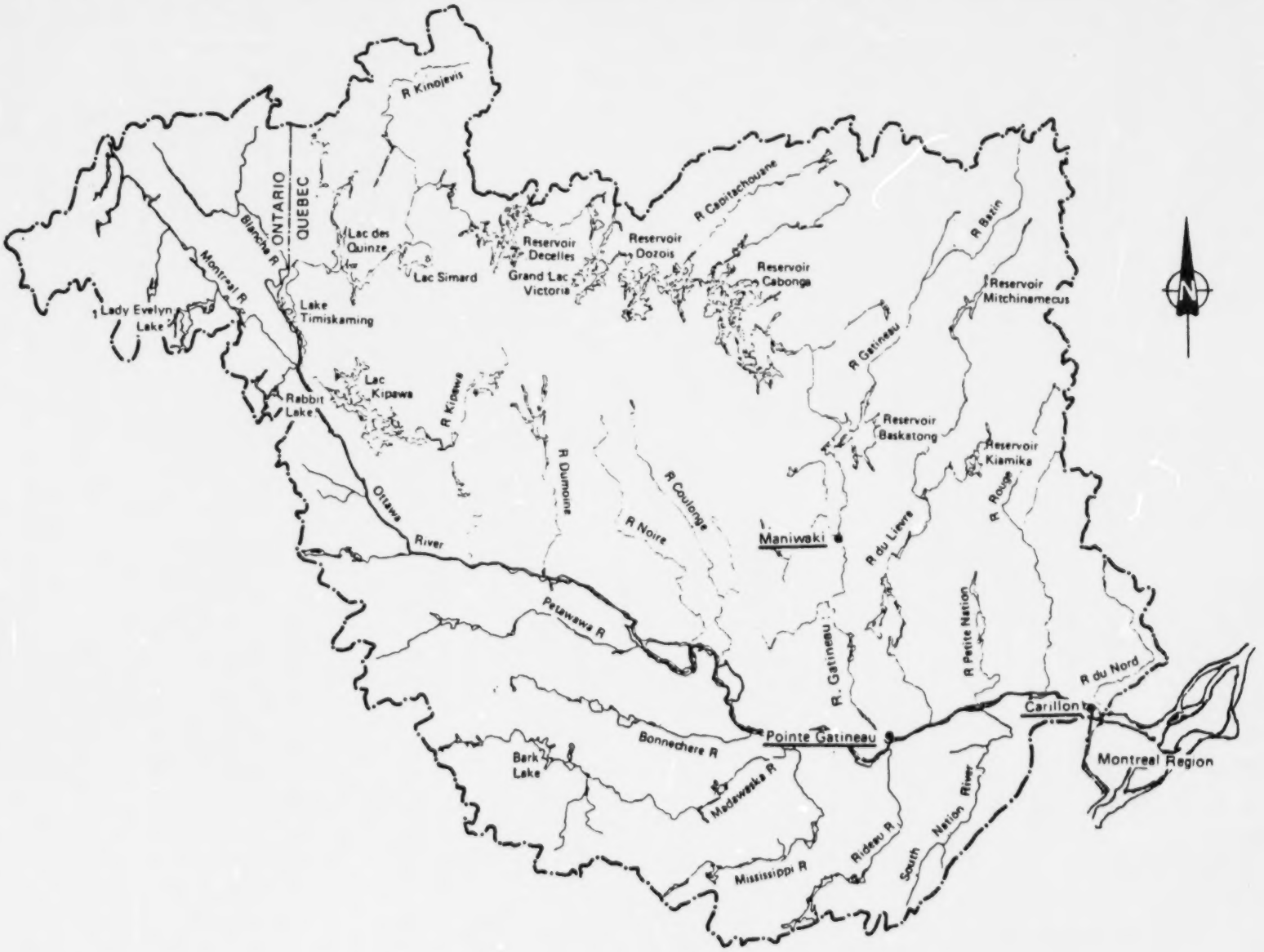

FIGURE 1 – THE OTTAWA RIVER BASIN

years. The peak flow reductions that have occurred have encouraged the gradual development of flood plain areas, and as a result, flooding is now a major concern. The Montreal Region, Maniwaki, and Pointe Gatineau, shown in Figure 1, are all located in Quebec and have been identified as being major flooding sites. The annual flood damages for the Montreal Region alone were estimated to be 2.5 million in 1974 dollars (Comité sur la Régularization des Eaux, Région de Montréal, 1976).

As a result of major floods in 1974 and again in 1976, the provincial and federal governments paid about 10 million dollars to compensate for the resulting flood damages. More than 50 percent of these compensation costs were provided to the municipalities of Maniwaki and Pointe Gatineau (Pêches et Environnement Canada, 1977).

The use of the reservoirs primarily for energy generation may not reduce the extent of flood damages under the most severe hydrologic conditions. Floods of long duration, such as that of 1947 which lasted from early April until the middle of July, cannot be significantly reduced by the existing reservoirs since under such conditions all reservoirs are filled before the end of the flood period. Similarly, when unexpected heavy rain occurs toward the end of the freshet season when reservoirs are already full or nearly so, such as in May and June 1974, little if anything can be done to provide much flood protection.

Although there are many reservoirs in the Ottawa River system, about 40 percent of the basin is still uncontrolled. Therefore flooding will continue to be a major concern, although the application of improved operating methods for the existing reservoirs may provide some protection.

3.0 THE RIVER REGULATION MODEL

The Ottawa River is operated by taking into account energy production, flood protection, navigation, low water problems, water quality needs, recreation, and log driving. However, the two major objectives that were identified are energy generation and flood protection. These two objectives are conflicting during years with high spring runoffs. Consequently, the RRM does a multiple-objective optimization of the system of reservoirs shown in Figure 2 by using a composite objective function (Corbu, 1977).

$$\text{Max } Z = C_1 Z_1 - C_2 Z_2 \qquad (1)$$

The first objective, Z_1, represents the worth of energy generation and is to be maximized, while the second objective, Z_2, represents flood damages and is to be minimized. The weighting coefficients C_1 and C_2 allow trade-offs between these two objectives.

If $C_1 = 1$ and $C_2 = 0$, the model will maximize only the worth of energy. Of course, some flood protection will be realized, but this will be as a by-product of the primary objective of energy production. Conversely, if $C_1 = 0$ and $C_2 = 1$, the model will minimize only the flood damages without any consideration for energy. In this case, there will clearly be some energy production, but this will be as a by-product of the primary objective of flood damage reduction. Obviously, there are an infinite number of alternatives between these two extremes and the model could be used

for any pair of C_1 and C_2 as long as $C_1 + C_2 = 1$, $0 \leq C_1 \leq 1$ and $0 \leq C_2 \leq 1$.

INDEX OF ABREVIATIONS

BK BASKATONG
BL BARK LAKE
BY BRYSON
CA CARILLON
CB CABONGA
CF CHUTES DES CHATS
CN CHENAUX
CR RAPIDES DES CEDRES
CS CHELSEA ET RAPIDES FARMERS
DJ DES JOACHIMS
DZ DOZOIS
HF HIGH FALLS (LIEVRE)
HU HULL II
J1 LOGICAL PLANT 1
KG KAMANISKEG
KM KIAMIKA
KW KIPAWA
LE LADY EVELYN
LN LOWER NOTCH
LV LAC VICTORIA
MB MATABITCHUAN
MC MOUNTAIN CHUTE
MD BARRETT CHUTE, CALABOGIE, STEWARTVILLE AND ARNPRIOR
MN MANIWAKI (LOGICAL PLANT)
MM MITCHINAMECUS
MR DUFFERIN CHUTE, ERCO AND MASSON
MT MISTINIKON
OH OTTO HOLDEN
PA PAUGAN
PG POINTE GATINEAU (LOGICAL PLANT)
QR RESERVOIR DES QUINZE
RI RAPIDE DES ILES ET PREMIERE CHUTE
RL RABBIT LAKE
RQ RAPIDE DES QUINZES
R2 RAPIDE II
R7 RAPIDE VII
TM TEMISCAMINGUE

FIGURE 2: THE OTTAWA RIVER CONFIGURATION

This optimization technique, known as the weighting method or the parametric method, was developed by Marglin (1962), and further discussed by Geoffrion (1967), Major (1969), Vemuri (1974), and Bishop et al. (1976). In reviewing the various methods used in multiobjective programming, Cohon and Marks (1975) showed that the weighting method is the most efficient for the case when the composite objective function is made up of only two objectives.

The energy objective, Z_1, requires a time horizon of 1 year. At the same time, the operation of the system requires daily guidelines on discharges from reservoirs. Because the utilization of an optimization technique to cover such a long time horizon with 1-day time periods is not possible due to the dimensionality of the resulting problem, a hierarchical approach was used. This approach allowed a large scale optimization problem to be solved in stages by a series of three models: long, mid, and short-term.

The long-term RRM is used to optimize the energy objective only (max $Z=Z_1$) and has variable length time periods, generally of 2 and 4 weeks. The mid-term RRM uses both objectives Z_1 and Z_2 and enables trade-offs between them. Its time horizon covers the longest historical spring freshet period of about 4 months with 1-week time periods. The short-term RRM has a time horizon of about 10 days and is used for the daily operation of the reservoirs. These three models are consistent with one another since the higher level models provide input to the lower level ones as shown in Figure 3. For operational purposes, the three models are run sequentially with updated runoff forecasts and the processes is rolled forward in time.

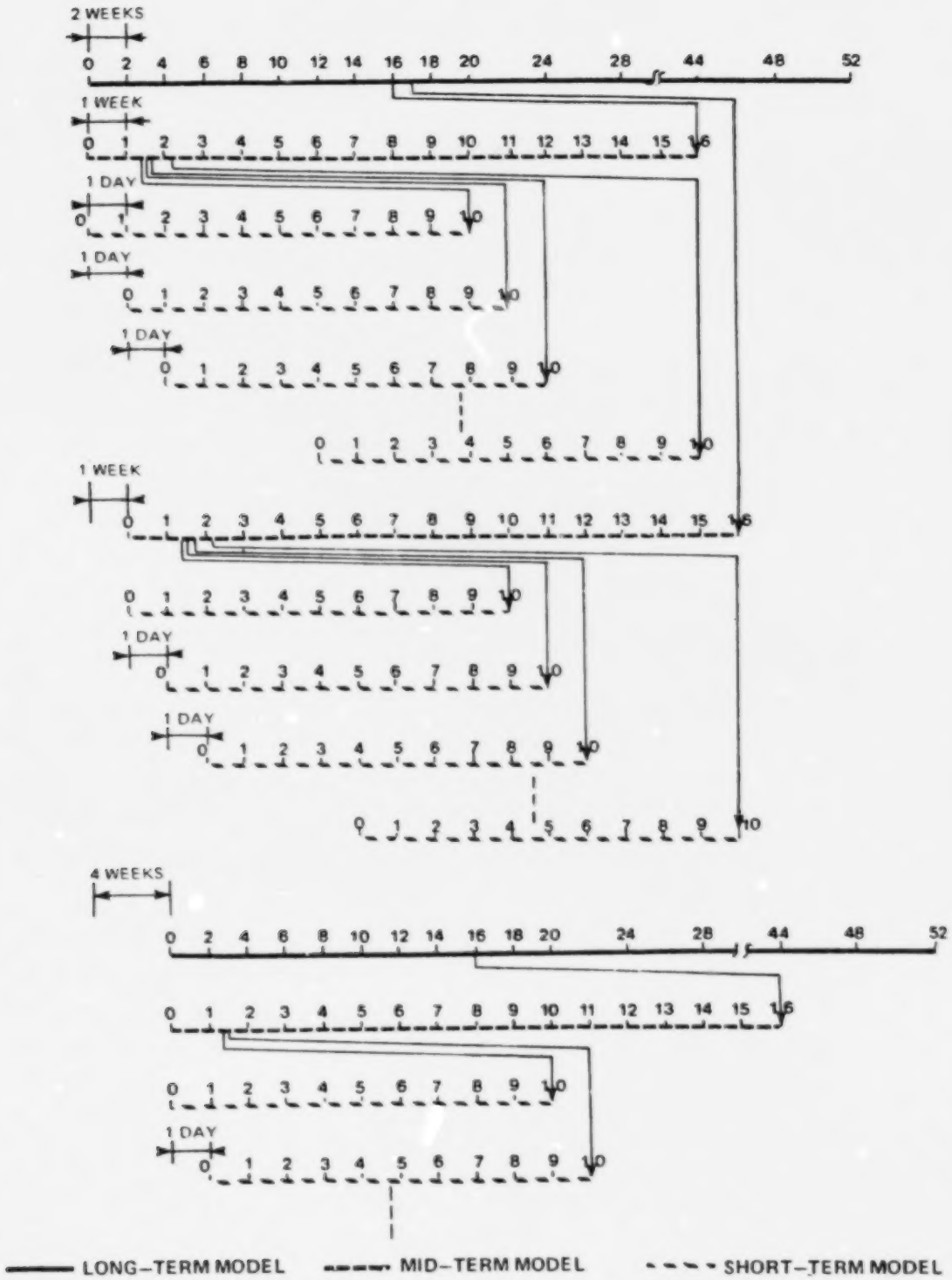

FIGURE 3: THE FORWARD ROLLING OF THE LONG, MID AND SHORT–TERM RIVER REGULATION MODEL

The large size and complex configuration of the Ottawa River system have favoured the utilization of the linear programming approach with separable programming capabilities. The MPSX/370 commercial software optimization package developed by IBM (IBM, 1979) was selected because it represents the state-of-the-art in linear and separable programming.

The natural runoff forecast input to RRM is provided at numerous points throughout the basin by the Runoff Forecasting Model (RFM) developed by Hydro-Quebec (Bisson, 1977). This is a deterministic model that transforms series of meteorological and climatological data into series of equally probable natural runoffs. From all series of forecasted natural runoffs, RRM uses the most likely natural runoff forecast which corresponds to a volume and peak, each with an exceedance probability of 50 percent. Such a forecast is not biased towards either of the two objectives of RRM and therefore allows for an equitable trade-off between energy generation and flood protection. Many more details about RRM are given by Bechard et al. (1981a, 1981b) and by Corbu and Thompson (1983).

4.0 TRADE-OFF BETWEEN ENERGY GENERATION AND FLOOD PROTECTION

As explained above, the mid-term RRM is used to enable DMs to make trade-offs between the two objectives (energy generation and flood damage reduction) during periods of high natural runoff. Since the RRM can be run with an infinite number of pairs of C_1 and C_2 coefficients, the DMs face the problem of selecting an acceptable pair of C_1 and C_2. This is equivalent to selecting a C_2 coefficient since $C_1 + C_2 = 1$. Also, since the mid-term RRM is usually run once or twice per week with updated natural runoff forecasts, DMs would have to meet frequently during the spring

freshet to select new C_2 coefficients. In the case of the Ottawa River there is another problem given the fact that DMs are from Toronto, Ottawa, Montreal, and Quebec, cities located far apart from one another. The trade-off methodology presented in this paper addresses these specific operating aspects as applied to the Ottawa River.

Figure 4 provides a graphical representation of RRM results. The vertical axis represents the worth of energy generated during the freshet season, ie, the objective Z_1, while the horizontal axis represents the flood damage reduction Z_2', which is a function of the second objective Z_2 ie, $Z_2' = f(Z_2)$. The concave downward curve shown in Figure 4 could be constructed by using the RRM results obtained for various C_2 values. This is a trade-off curve and is also known as the noninferior set or the Pareto optimal set (Bishop, 1976).

The trade-off curve represents the boundary of feasible alternative solutions between the two objectives Z_1 and Z_2. Any point lying inside the trade-off curve toward the origin such as the point C is a feasible solution. However, any such point corresponds to a solution that is worse than at least one other point on the trade-off curve. In Figure 4, for example, point A represents a better solution than point C since for the same degree of flood damage reduction, a higher energy value occurs. Similarly, point B, located on the trade-off curve, also provides a better solution than point C since for the same level of energy generation the flood damage reductions are higher.

All the points on the curve represent an optimum utilization of the available water resources in the Ottawa River Basin in respect of the two objectives. However, for each point on the curve, there is a

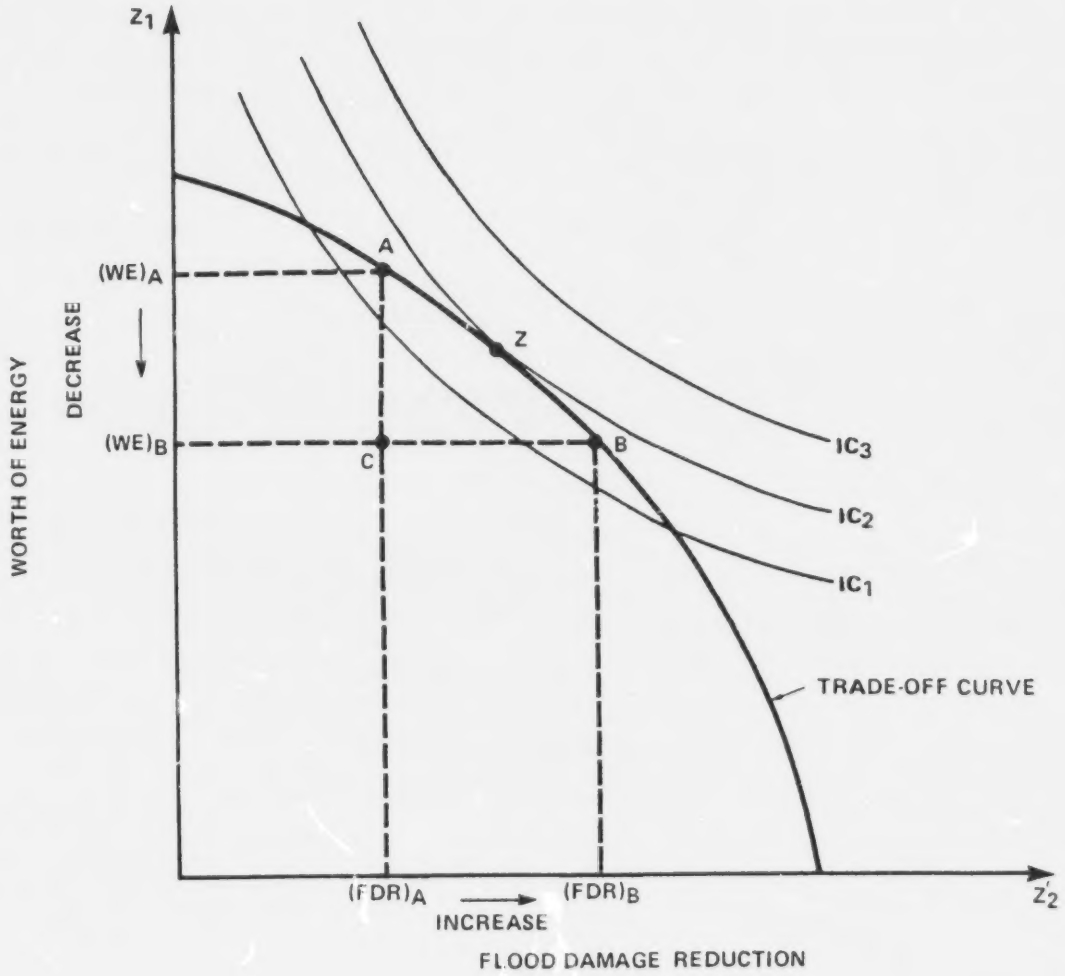

FIGURE 4: TRADE-OFF CURVE FOR THE OTTAWA RIVER BASIN

definite split of the total benefits between flood reduction and energy generation. It can be easily seen that, between any points which are located on the trade-off curve, such as A and B in Figure 4, increases in one objective occur only at the expense of the other objective. The task of the DMs, therefore, is to select from all the points located on the trade-off curve the particular point that is the "optimal" alternative.

To this end, a knowledge of society's preferences in terms of energy generation and flood protection is required. Such a function can theoretically be represented in Figure 4 by the indifference curves IC. Those IC curves lying further from the origin represent a higher level of social satisfaction. The point of tangency, Z, of one of the IC curves with the trade-off curve indicates the optimal alternative or the "best compromise solution" (Belenson, 1973). However, the indifference curve as an aggregate representation of society's values and preferences as perceived by DMs is very difficult, if not impossible, to quantify for practical applications.

The remainder of this section focuses on a methodology that allows DMs to determine the point Z corresponding to the best trade-off alternative between the objectives Z_1 and Z_2.

Studies performed earlier with RRM have confirmed that for small C_2 coefficients, an increase in the value of C_2 results in flood reduction benefits that are larger than the corresponding losses in energy generation. This difference between the total flood damage reduction and its corresponding loss of energy that is obtained for a particular C_2 can be defined as a net benefit to society as a whole despite the fact that the beneficiaries of flood damage reductions are not necessarily the same as the beneficiaries of improved energy generation.

To obtain the net benefit it is necessary to first run RRM with $C_2 = 0$. The corresponding values of the two objectives, ie,

energy generation and flood damage reduction, are noted as $Z_{1,0}$ and $Z_{2,0}$. RRM is then run again with a coefficient $C_2 = C \neq 0$ with $Z_{1,C}$ and $Z_{2,C}$ noted as the corresponding values of the objectives. The difference $Z_{1,0} - Z_{1,C}$ represents the decrease in the worth of energy generated during the freshet season when the coefficient C_2 is increased from 0 to C. Similarly, the difference $Z_{2,0} - Z_{2,C}$ represents the benefits obtained by reducing the flood damages when C_2 is increased from 0 to C. The net benefit (NB) of operating the Ottawa River with a $C_2 = C$ is given by the relationship:

$$NB_C = (Z_{2,0} - Z_{2,C}) - (Z_{1,0} - Z_{1,C}) \qquad (2)$$

Different values of the net benefit NB_C can be obtained if the value of the C_2 coefficient is changed.

The C_2 coefficient for which the net benefit is maximum, can be obtained by writing:

$$\frac{\partial(NB_C)}{\partial C_2} = 0 \qquad (3)$$

By substituting the net benefit relationship (2) in equation (3), we obtain:

$$\frac{\partial Z_{1,C}}{\partial C_2} = \frac{\partial Z_{2,C}}{\partial C_2} \quad \text{or} \quad \frac{\Delta Z_{1,C}}{\Delta C_2} = \frac{\Delta Z_{2,C}}{\Delta C_2} \qquad (4)$$

In other words, the net benefit becomes maximum for that value of C_2 for which a small increase in its value will generate a benefit in flood reduction equal to the resulting loss in energy production.

In practice, the maximum net benefit was found by repeatedly running RRM with predefined, continuously increasing C_2 coefficients. The C_2 coefficient corresponding to the maximum net benefit can be referred to as the optimum C_2, while the corresponding Z_1 and Z_2 values of the two objectives represent the best trade-off alternative. The maximum net benefit trade-off method is known in the theory of multiobjective analysis and has been discussed by Major (1977). It should be emphasized that this solution, although economically efficient, can represent the best trade-off only if the maximum net benefit concept is socially and politically acceptable as well. The reason for this, as stated earlier, is that the beneficiaries of the flood damage reduction and energy generation are not necessarily the same population. This point will be discussed in a subsequent section.

A numerical example of the methodology described above may be provided by using data from the ORRPC Final Report (ORRPC, 1980) for three historical years with serious floods (1960, 1974, and 1976). Each of these 3 years represents a different hydrological condition characterized by high runoff contribution from different parts of the Ottawa River Basin to the peak flow at Carillon that is important for assessing flood damages in the region of Montreal.

The basic assumptions considered in the analysis are as follows:

(a) The mid-term RRM was used with historical natural runoffs considered to be perfect forecasts. This reduced the high computer costs associated with the simulation of the forward rolling procedure described earlier.

(b) Six C_2 coefficient values were used: 0.0, 0.5, 0.67, 0.75, 0.91, and 0.95;

(c) The initial and the target end-of-freshet storage levels were represented by actual data;

(d) The value of electrical energy was considered to be $20/MWh; and

(e) The flood damage curves for Montreal, Maniwaki, and Pointe Gatineau, the three flooding sites incorporated in the objective function of the model, included only residential damages and did not take into account any social effects and their costs.

The trade-off curves obtained by running RRM for the three flood years are shown in Figure 5. The points on the curves show the RRM optimum solutions for the given C_2 values. It is obvious from this figure that the hydrologic conditions have a significant effect on the value of the two objectives as well as on the shape of the trade-off curves.

The total energy losses and the flood damage reductions are shown in Figure 6 as a function of the C_2 coefficient for each of the selected years. These graphs illustrate that over a large range of C_2, the reduction in flood damage is larger than the corresponding loss of energy production. They also show that, for some years, there is a point beyond which increases in C_2 produce losses in energy production for no significant gain in flood damage reduction.

The net benefit for a particular C_2 coefficient is the difference between the dashed line and the continuous line in Figure 6. These net benefits are plotted versus the total flood damage reduction in Figure 7, which shows that the C_2 coefficient for which the net benefits are maximized correspond to $C_2 = 0.50$ (1960 and 1974) and $C_2 = 0.56$ (1976). These are the optimum C_2 coefficients under the given conditions. The location of these best trade-off solutions on the trade-off curves shown in Figure 5 is indicated by an arrow.

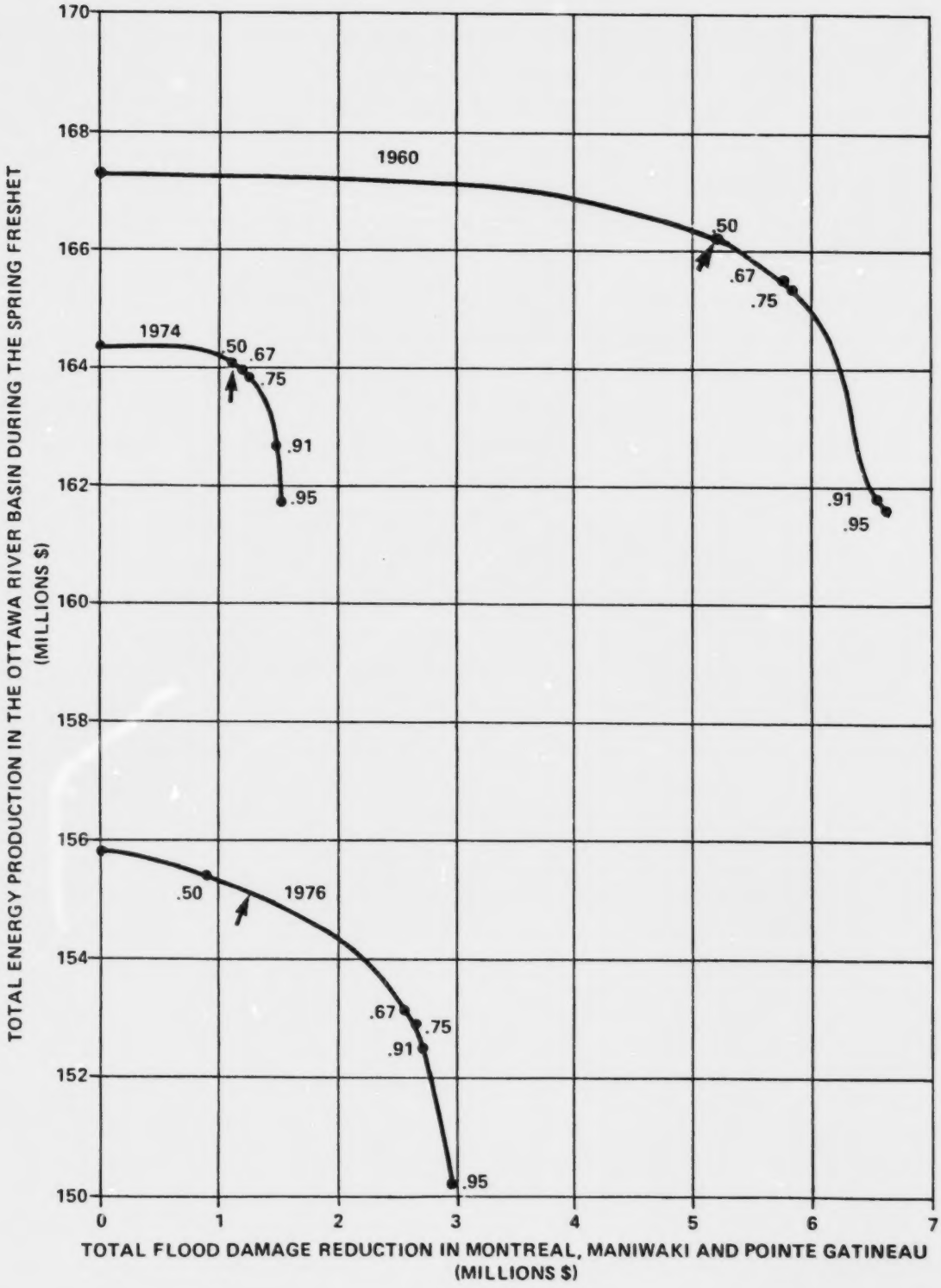

FIGURE 5: THE TRADE-OFF CURVES OF THE OTTAWA RIVER SYSTEM FOR THE 1960, 1974 AND 1976 FRESHET

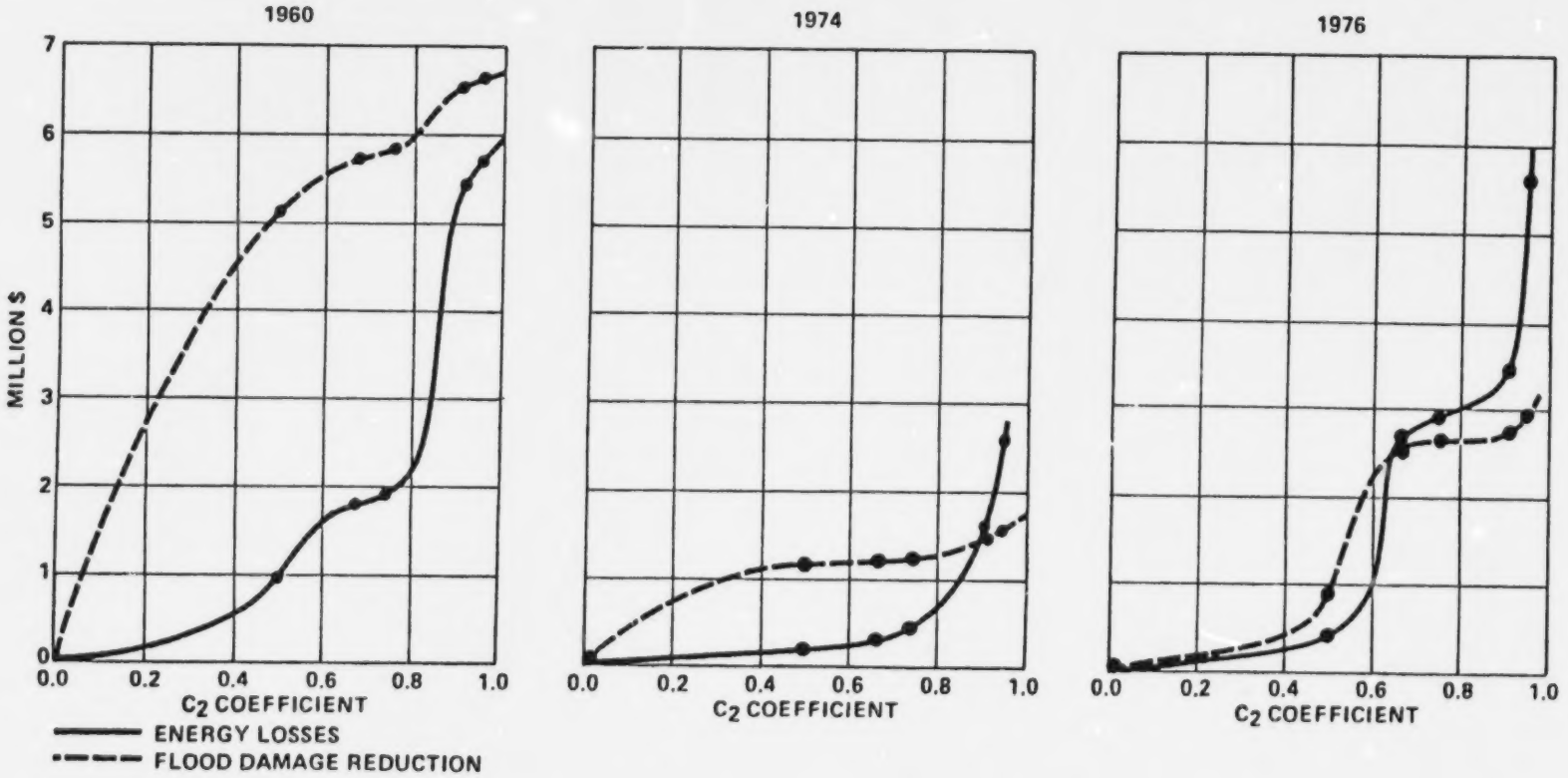

FIGURE 6 – TOTAL ENERGY LOSSES IN THE OTTAWA RIVER BASIN COMPARED TO TOTAL REDUCTION OF FLOOD DAMAGES IN THE REGION OF MONTREAL, MANIWAKI AND POINTE GATINEAU

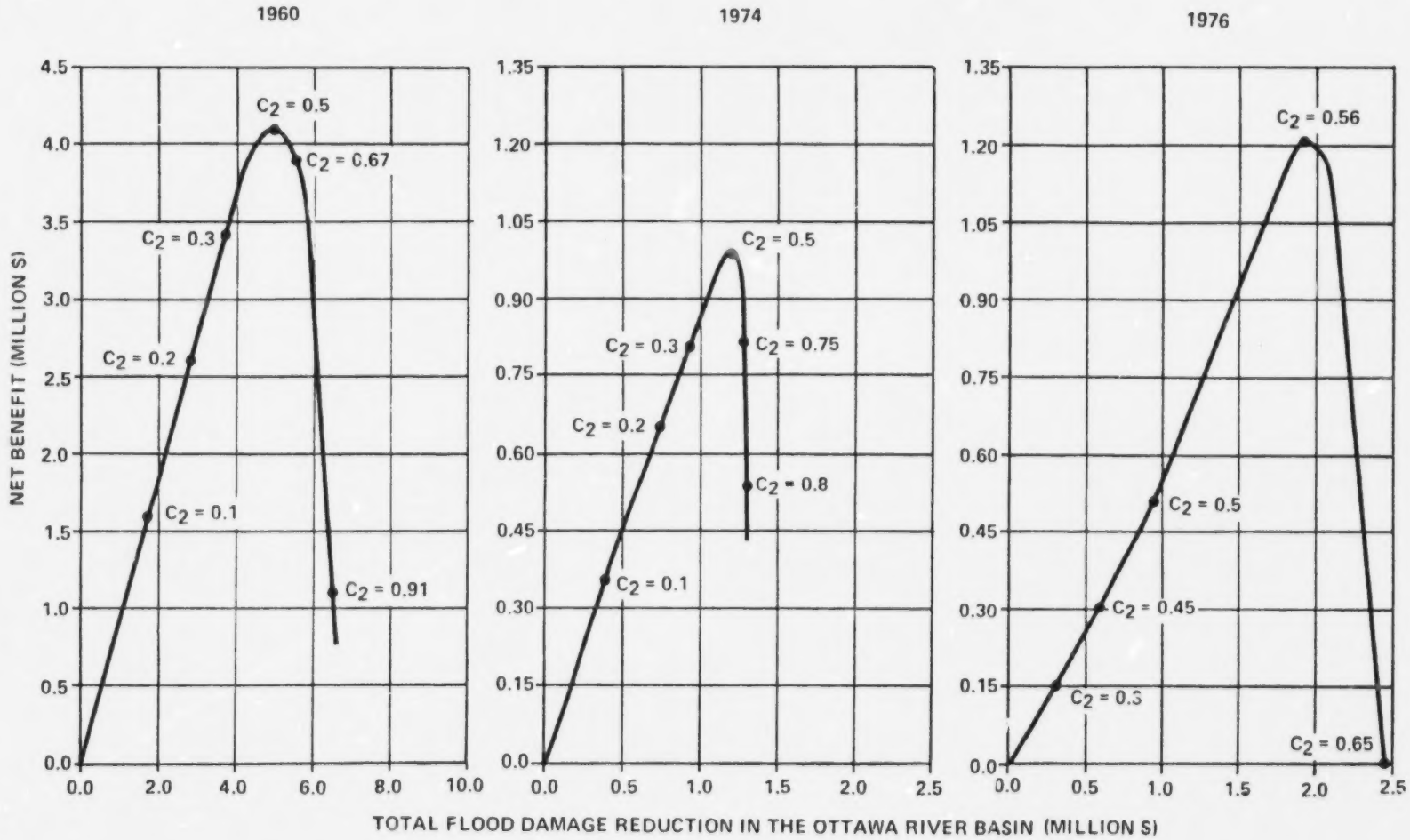

FIGURE 7: GRAPH SHOWING THE OPTIMUM C_2 COEFFICIENT

Figure 8 shows that the energy losses corresponding to the best trade-off solution are rather small in percentage terms (0.2 percent loss of the energy generated during the freshet season for the entire system), but this would represent a substantial contribution ($1 million per year for years with high natural runoffs) towards flood protection in an overall integrated approach to the operation of the Ottawa River.

The results of the above analysis, ie, $C_2 = 0.5$, was accepted and used by ORRPC during the spring freshet seasons of 1982 and 1983.

The literature on multiobjective decision- making methodologies is substantial and many methods have been developed. The concordance analysis or Electre method (Nijkamp and Vos, 1977), the stochastic trade-off approach (Croley II and Rao, 1979), the two-stage matrix method (McBean and Zukovs, 1983), the SEMOPS method (Monarchi et al. 1973), the compromise programming method (Duckstein and Opricovic, 1980), PROTRADE (Goicoechea et al., 1979) and the surrogate worth trade-off method (Haimes and Hall, 1974) have been developed and applied to various water resources problems. These methods are most appropriate for the design and planning process since they require the continuous intervention of the DMs.

The methodology described has the main advantage that once accepted, DMs do not need to meet during the spring season to analyze the results from each mid-term RRM run with updated natural runoff forecasts and decide on a new C_2 coefficient. The mid-term RRM will automatically generate the stream flow forecast and reservoir regulation plan corresponding to the optimum C_2.

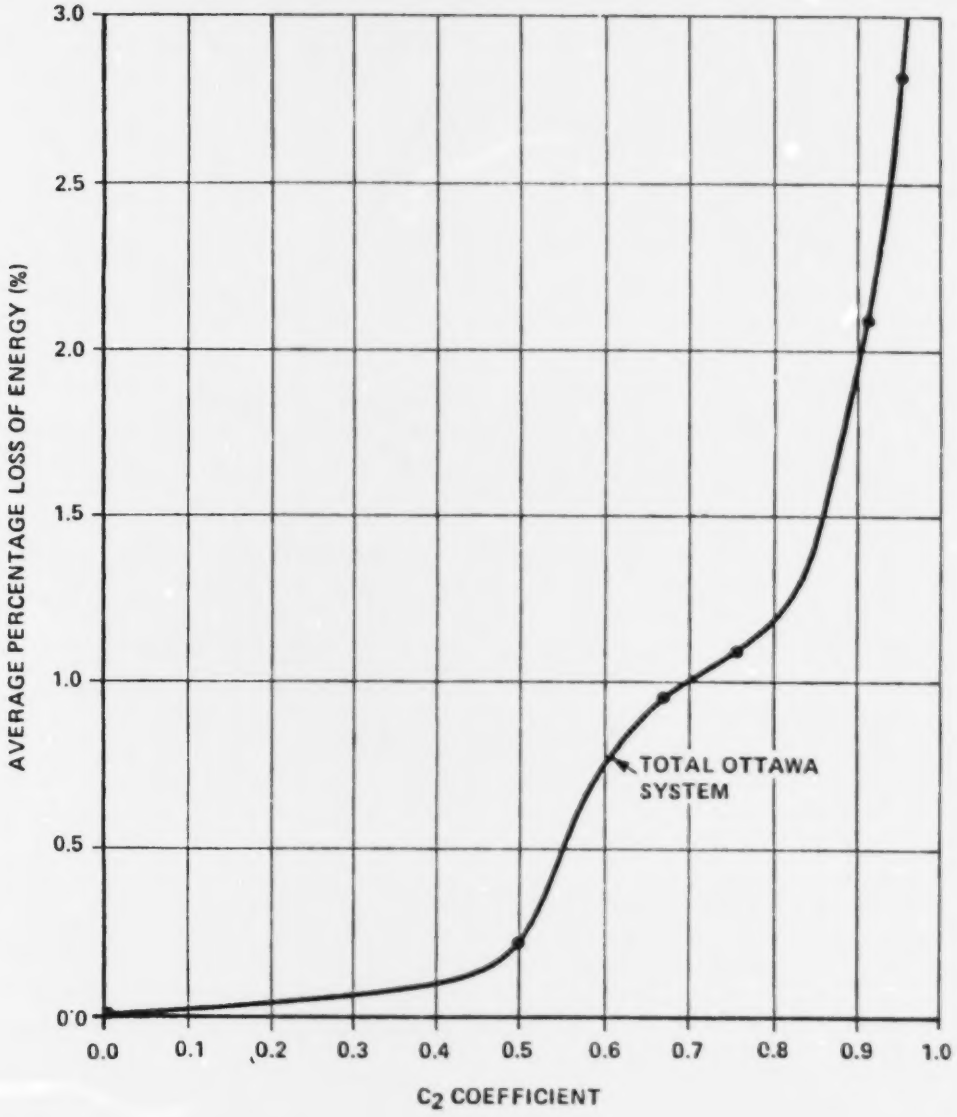

FIGURE 8: AVERAGE PERCENTAGE LOSS OF ENERGY VERSUS THE C_2 COEFFICIENT FOR THE 1960, 1974 AND 1976 RUNOFF DATA

Consequently, the method is most appropriate to an operating environment involving a multiobjective river system that requires frequent decisions to be made.

5.0 DISCUSSION

An important aspect touched on briefly in the foregoing is the political acceptability of the maximum net benefit methodology as applied to the Ottawa River. In general the flooding affects only a small part of the population, but the damaging effects on an individual is highly visible and long lasting. Those affected generally become highly vocal and put high pressure on politicians to solve the flooding problem. On the other hand, changing the operation of a river in order to reduce the risk of flooding often has a detrimental impact on the cost of energy. This additional energy cost, however, is shared by a large population, ie, all electricity users, and the impact on an individual user is almost undetectable and consequently, is not likely to trigger any political pressure. It is, therefore, obvious that to the decision makers, a "flood protection" dollar is not equal to one "energy generation" dollar.

To account for the different weights of these two objective oriented dollars, the maximum net benefit trade-off methodology can be applied by substituting relationship (2) with relationship (5).

$$NB_C = (Z_{2,0} - Z_{2,C}) - C_3(Z_{1,0} - Z_{1,C}), \text{ where } 0 < C_3 \leq 1 \qquad (5)$$

By using this more general formula, equations (4) become:

$$\frac{\partial Z_{2,C}}{\partial C_2} = C_3 \frac{\partial Z_{1,C}}{\partial C_2} \quad \text{or} \quad \frac{\Delta Z_{2,C}}{\Delta C_2} = C_3 \frac{\Delta Z_{1,C}}{\Delta C_2} \qquad (6)$$

The C_3 coefficient is effectively a conversion factor between the the "energy generation" dollar to the "flood damage" dollar in very much the same way as the currency exchange rate between the Canadian dollar and the US dollar for instance.

By using the C_3 coefficient, a means of reducing the value of the "energy generation" dollar as compared to the "flood protection" one is introduced. As the value of C_3 decreases, the relative value of the "flood protection" dollar increases and the best trade-off alternative will correspond to a higher C_2 coefficient. An example of the impact of the C_3 coefficient on the optimum C_2 values is shown in Figure 9.

In general, application of the maximum net benefit trade-off method with $C_3 < 1$ will provide additional benefits to the flood protection objective in comparison with the $C_3 = 1$ case. However, the incremental monetary worth of these benefits will be lower than the corresponding monetary losses incurred by the energy generation objective.

The question that arises, then, is: "What value should be given to C_3 in the Ottawa River case?" If the entire Ottawa River basin were located in one province, determining the relative value of the "energy generation" dollar to the "flood damage" dollar would be more localized and simpler to solve. New dimensions to the problem appear in the actual case when two provinces are involved since, in such a case, the decision is not limited to one province or the other. The authors claim no particular wisdom in answering this question. However, it is our opinion that once a value for the C_3 coefficient is accepted, then the maximum net benefit trade-off method could lay the foundation for determining the optimum value of C_2 as illustrated in Figure 9 for use in the operation of the Ottawa River that will satisfy flood reduction and energy generation interests in both provinces of Ontario and Quebec.

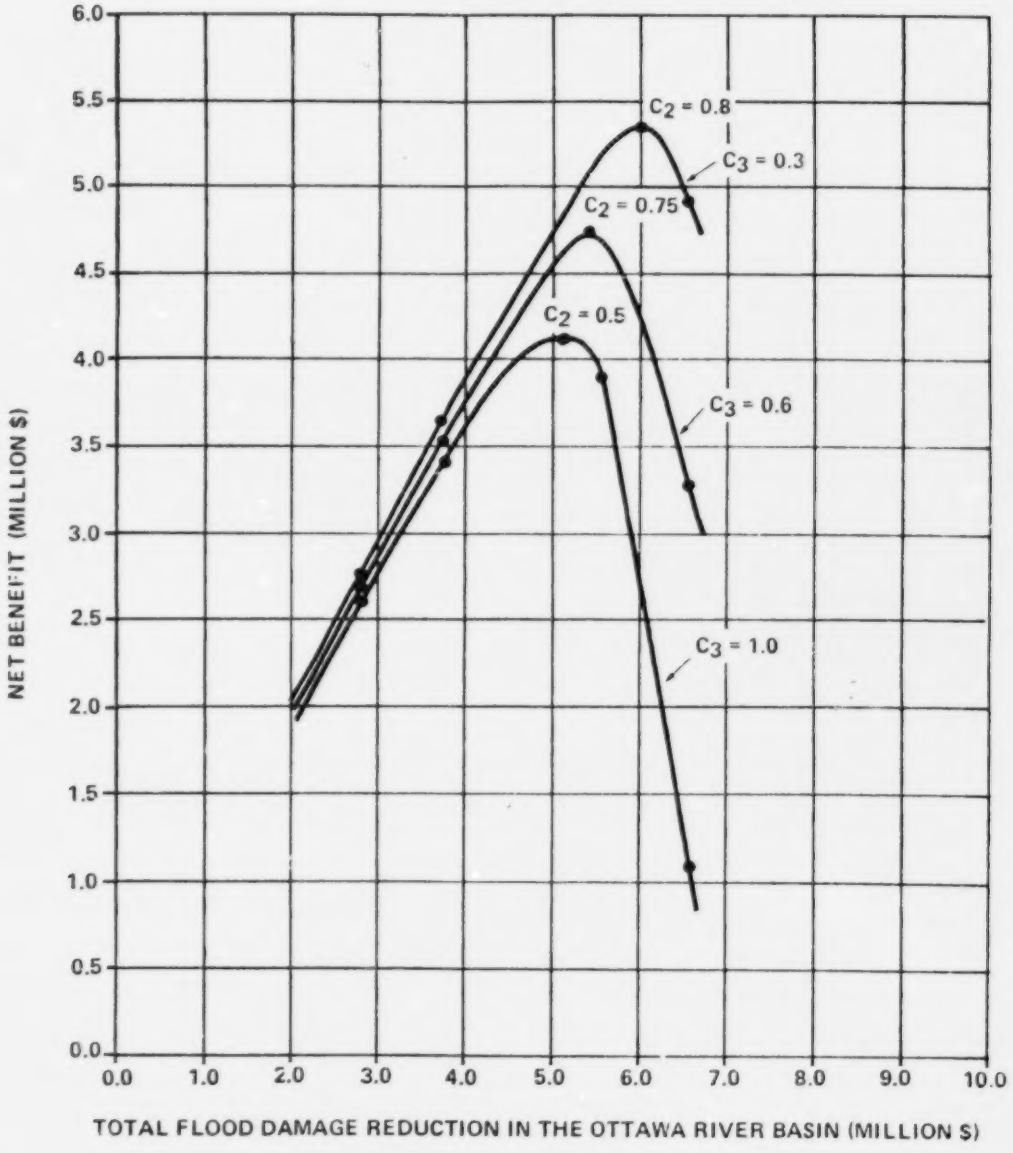

FIGURE 9: OPTIMUM C_2 COEFFICIENT VALUES WHEN THE MAXIMUM NET BENEFIT TRADE-OFF METHOD IS APPLIED WITH $C_3 = 1.0$, $C_3 = 0.6$ & $C_3 = 0.3$ (1960)

A second difficulty in utilizing this trade-off method for the Ottawa River basin, or for that matter, the utilization of the RRM model itself, is the noncommensurability of flood damages. The social cost function associated with various levels of flooding is very difficult to estimate. Much of the pricing theory in economics is devoted to the question of translating physically noncommensurable quantities into monetary units, but the problem seems far from being solved. Despite the lack of a generally accepted methodology, there are in actual life large numbers of people who are making monetary estimates for noncommesurable quantities in their day-to-day decisions. It is therefore felt that DMs involved in the Ottawa River basin will be able to agree on an estimate for the social cost function associated with flooding. The modern nonquantitative techniques for treating social concerns could be of help in this respect.

6.0 CONCLUSIONS

The River Regulation Model developed by the Ottawa River Regulation Planning Committee was used with different C_2 coefficients to study the noninferior set of trade-off alternatives between energy generation and flood protection objectives that were identified in the Ottawa River case.

The application of the maximum net benefit methodology described in this paper allows decision-makers to identify the best trade-off alternative between the two objectives under continuously changing hydrologic conditions. The methodology has the advantage that it is well suited to the specific operational environment of a multipurpose, multiobjective river system and does not require the continuous presence of the decision-makers. Furthermore, the methodology can be easily computerised and included in the River Regulation Model.

The utilization of the maximum net benefit trade-off methodology described in this paper to the Ottawa River cannot by itself solve the flooding problem. Floods will still occur. However, combining in a cost-efficient way such an operating trade-off approach with engineering, administrative and legal measures will ensure that a high level of flood protection is achieved at minimum cost. To this end, the eventual cost of reducing the flood damages by modifying the operation of the river (ie, using RRM with $C_2 \neq 0$ instead of $C_2 = 0$) should be compared to the cost of other means of reducing the flood damages such as building new reservoirs, channel improvement, rezoning, and the like.

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FUNDAMENTAL PROBLEMS IN STREAMFLOW FORECASTING

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Streamflow forecasting models are made up of hydraulic, meteorological and hydrological components. The three categories differ significantly in the reality of their scientific underpinning and in the importance of their contributions to the forecasting process. It is contended herein that the hydrologic components have the greatest potential for producing realistic and useful forecasts but that this potential is unlikely to be realized because of the lack of research into hydrologic processes.

The hydraulic components of forecasting models are applied to the water after it reaches the major river channels. They have a good scientific basis in the laws of conservation of mass, energy and momentum and in well established approximations such as Chezy's law. Furthermore they have some limited use for short-term flood forecasts on large river systems when there is no rainfall and/or snowmelt and when evapotranspiration rates are relatively stable. Thus they may permit effective flood warnings and a limited amount of storage control. However, if the inputs to the basin are changing, if the basin is small or if longer forecasts are needed, there is a need to take into account meteorological and hydrological factors.

The meteorological inputs to streamflow forecasting are the provision of up-to-date information on precipitation, temperature and radiation over the river basin and the provision of forecasts of rainfall and temperatures for the basin. Great progress is being made in the provision of current meteorological information through the use of automated sensors, data collection platforms and remote sensing. In contrast, the meteorological forecasts remain short-term and of questionable reliability and the prospects for significant improvement seem remote. Furthermore, the utility of improved meteorological forecasts in streamflow forecasting depends on our knowledge of the hydrologic processes that transform precipitation (rainfall and snowmelt) into evapotranspiration and runoff.

In the light of the foregoing considerations it is apparent that the hydrologic components offer the only real hope for providing forecasts with enough lead time to operate reservoirs or to take other remedial action in anticipation of either floods or droughts. Such forecasts depend on a determination of antecedent moisture conditions (the amount of water stored in the snowpacks, lakes and swamps, aquifers and unsaturated soils of the basin) which control the response of the basin to any subsequent rainfall or snowmelt event. Thus the probability of a flood is much greater when the basin is wet than when the basin is dry and the probability of a drought is much greater when the basin is dry than when the basin is wet.

With the expenditure of much manpower and money it is possible to monitor the changes in the amount of water stored in the snowpacks, lakes and swamps and in the groundwater systems of the basin. However the resources required to monitor adequately the changes in the amount of water stored in the most important reservoir, the unsaturated soil, are too horrendous to contemplate except in a research context. Therefore attempts to take antecedent conditions into account usually focus on the modelling the hydrological cycle either by working forward with a continuous water budget or by working backward with the model to establish antecedent conditions at some recent point in time from both the observed input and the observed output (runoff) up to that time. Such models usually include attempts to reflect the effects of antecedent moisture on the runoff response.

It is obvious from the foregoing considerations that streamflow forecasting requires a good knowledge of hydrological processes. Unfortunately such knowledge is either unavailable or is unknown to those who formulate and use the models. The only concepts used in hydrological modelling that have a firm basis in reality are the laws or conservation of mass, energy and momentum. Even that cornerstore of modern river hydrology, the unit hydrograph, is based on the assumption of linearity - an assumption that has been recognized as a crude assumption at best for over two decades. Under such circumstances the hydrological components are merely conglomerations of plausible but untested assumptions depending for results on the calibration (or fudging) of numerous coefficients that have a dubious basis in reality.

The fundamental problems in hydrological modelling have been dealt with in some detail in a theme paper entitled "Integrated basin response - a problem of synthesis or a problem of analysis?" which was presented at Canadian Hydrology Symposium: 82 in Fredericton in June, 1982. A copy of the paper, which was published in the Proceedings, is attached and recommended for reading. Among other points of interest to those who formulate and use hydrological models, it includes:

(1) A literature review and a detailed evaluation of the assumptions concerning the soil-plant-atmosphere system that underly the evapotranspiration estimates in the SACRAMENTO WATERSHED MODELLING SYSTEM. The review and evaluation demonstrate how seemingly plausible and straightforward assumptions can be diametrically opposed to reality because of little known feedback mechanisms and interactions.

(2) Evidence that there is a great deal of hydrological knowledge hidden in the botanical, soil science, hydrogeological and meteorological literature; that this knowledge could provide the basis for improvements in streamflow forecasting; and that this knowledge has been studiously ignored.

Practically all of what now passes for hydrological knowledge can be traced back to the conventional wisdom, misconceptions and superstitions

of twenty to thirty years ago. This is probably because it became imbedded, in mathematically tractable form, in conceptual mathematical models. The time and effort invested in such models tends to deter the hydrological community from searching for new knowledge or from supporting fundamental research because positive results might be less tractable mathematically and might even show up the weaknesses of the models. In the meantime the science of hydrology is becoming more and more an academic exercise, remote from reality, with no satisfactory answers to real problems such as the need to forecast the hydrologic responses of river basins to specific precipitation events and the need to predict the hydrological effects of man-made or natural changes.

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• CANADIAN HYDROLOGY SYMPOSIUM: 82
• ASSOCIATE COMMITTEE ON HYDROLOGY
NATIONAL RESEARCH COUNCIL OF CANADA
• JUNE 14-15, 1982
FREDERICTON, NEW BRUNSWICK

• SYMPOSIUM CANADIEN D'HYDROLOGIE: 82
• COMITÉ ASSOCIÉ D'HYDROLOGIE
CONSEIL NATIONAL DE RECHERCHES CANADA
• LES 14 ET 15 JUIN 1982
FREDERICTON, NOUVEAU-BRUNSWICK

INTEGRATED BASIN RESPONSE - A PROBLEM OF SYNTHESIS OR A PROBLEM OF ANALYSIS?

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ABSTRACT

Integrated basin response is usually considered to be a problem of synthesis or of modelling. This attitude is understandable because of the difficulty of analysis and because of the need to obtain results that may be of use in water planning and management or in environmental impact studies. However it is based on the supposition that most hydrological processes and interactions are well understood and only need to be brought together in a workable model. This supposition is evaluated by a critical review of the conventional conceptual techniques for estimating evapotranspiration as exemplified in the SACREMENTO WATERSHED MODELLING SYSTEM. The review shows that currently accepted procedures for estimating this important component of the hydrological cycle are riddled with assumptions that contravene published theoretical knowledge and empirical evidence. It also indicates that an approach based on synthesis puts more stress on mathematical tractability than on reality and thereby serves as a deterrent to improved understanding of hydrological processes and interactions.

An analytical approach requires observations or reliable estimates of the major water balance components for an entire drainage basin. Observed runoff and precipitation that has been areally averaged meet this requirement. Furthermore the development of the complementary relationship now permits areal evapotranspiration to be estimated from its effects on the routine climatological observations needed to compute potential evapotranspiration. This means that the remaining major component in the water balance, the stored water, can be analyzed and evaluated. Examples show how this capability can provide the basis for the improved understanding of hydrological interactions and integrated basin response that is required before synthesis-oriented or modelling research can again become productive.

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INTRODUCTION

Integrated basin response may be interpreted in a number of different ways. Presumably it refers to the runoff from a basin, which is the product of many different processes and interactions in the soil-plant-atmosphere continuum and of their spatial variations. It has been customary in hydrology to treat it as a problem of synthesis or of modelling and this is clearly evident in the papers to be presented during this session.

The analytical approach to integrated basin response has been neglected for a number of reasons. The two most important ones are that the information obtained from laboratory and plot experiments may not be relevant on a basin scale and that it has not until now been possible to analyze basin water balances with reliable independent estimates of the most important components. However the latter constraint has now been relaxed sufficiently to make it worthwhile to expend more research effort on analysis.

The emphasis on synthesis and model formulation in hydrology is understandable in the light of the previously mentioned analytical difficulties and of the need for results that may have some use in water planning and management and in environmental impact studies. Furthermore it is expected that the emphasis will continue in the future. However the concentration of research effort on synthesis and modelling, without the fresh insights and improved concepts that can only come from analysis, has had and will continue to have an unfortunate effect on the science and practice of hydrology. For this reason the views presented herein concentrate on the weaknesses of the synthesis-oriented approach and on the potential strengths of the analytical approach.

WEAKNESSES OF SYNTHESIS-ORIENTED APPROACH

General

The synthesis-oriented approach presupposes that most hydrological processes and interactions are well understood and only need to be brought together into a workable model of integrated basin response. This is its major weakness because the only concepts used in hydrology that have a firm basis in reality are the law of conservation of mass, the law of conservation of energy and approximations to the law of conservation of momentum such as those represented by the Darcy formula and modifications to the Chezy formula. Even that cornerstone of modern river hydrology, the unit hydrograph, is based on the assumption of linearity - an assumption that has been recognized as a crude approximation, at best, for over two decades. Under such circumstances the models of integrated basin response are simply conglomerations of plausible but untested assumptions that rely for results on the calibration (or fudging) of numerous coefficients with a questionable basis in reality.

Much of the lack of reality in watershed models is due to the large number of interactions and feedback mechanisms in the soil-plant-atmosphere continuum. Those that are known tend to be ignored and there is reason to believe that many others remain unidentified. The problem is compounded by the lack of communication between scientific disciplines. Thus many of the processes and interactions in watershed models are incompatible with findings

published in the meteorological, botanical and soil science literatures. This is explored in depth using as an example the conventional conceptual techniques for estimating evapotranspiration that are employed in the modelling of integrated basin response.

The currently accepted conceptual techniques for estimating evapotranspiration have many applications, all of them slightly different. Examples are in Budyko (1974), in the new versatile soil moisture budget presented by Baier and Robertson (1966) and in a technique used by the United Kingdom Meteorological Office to map soil moisture deficits and actual evapotranspiration (Grindley, 1970). Despite superficial differences the basic assumptions are the same and can be evaluated by examining one example, in this case the technique used in one of the better known watershed models.

The SACRAMENTO WATERSHED MODELLING SYSTEM (Burnash, Ferrel and McGuire, 1973) employs five conceptual storage reservoirs in the soil-plant continuum, two of which store tension water and three of which store free water. The tension storages are emptied by evapotranspiration and filled by interception or percolation whereas the free-water storages are emptied by interflow, baseflow or subsurface outflow and are filled by infiltration or percolation. There are also transfers of water from free-water storage to tension storage. All of these processes depend on the proportional loading (i.e. the ratio of current storage to storage capacity) for one or more of the reservoirs. The storage capacities and the parameters that control the transfers of water to and from the reservoirs are calibrated to provide the best possible fit between model output and recorded streamflows. The evapotranspiration is assumed equal to the evaporation demand (normally represented by pan evaporation or potential evapotranspiration) multiplied by the difference between the sum and product of the proportional loadings for the total tension storage and the upper zone tension storage. Because it abstracts a large proportion of the total precipitation directly from the tension storages and indirectly from the free-water storages, the need to adjust the evapotranspiration to make the water-balance balance over the calibration period has a dominant influence on the selection of storage capacities and transfer parameters. Therefore the reality of the calibrated capacities and transfer parameters, i.e. their ability to simulate flows before and after the calibration period and their applicability to the development of relationships for transposition to other basins, depends to a large extent on the validity of the assumptions used in estimating evapotranspiration.

The technique used for estimating evapotranspiration in the SACRAMENTO WATERSHED MODELLING SYSTEM is based on a number of implicit assumptions about soil, plant and atmospheric processes. The discussion that follows furnishes published experimental evidence that these are either wrong or questionable.

Soil Assumptions

The tension storage capacities are supposed to reflect the amount of moisture that can be held in the root zone between an upper threshold value of moisture content (e.g. the field capacity) and a lower threshold value of moisture content (e.g. the wilting point). The specific assumptions that are made in modelling the tension storages are:

(1) That the tension storages are constant and do not depend on seasonal or annual changes in vegetation cover and root development. The problems inherent in this assumption are self-evident and are particularly important in cultivated areas.

(2) That there is no drainage from tension storage when the water content is below the upper threshold value, the field capacity. This assumption is contrary to the theoretical and experimental findings of Rubin and Steinhardt (1963), Rubin, Steinhardt and Reiniger (1964) and Rubin (1966) that soil water content during rain infiltration rises only to the point where the hydraulic conductivity becomes equal to the rainfall or snowmelt rate and then water is transferred downward. Thus it is possible to have significant groundwater recharge from long periods of rainfall or snowmelt with the water content well below field capacity. Moreover, evidence provided by Robins, Pruitt and Gardner (1954), Ogata and Richards (1957), Neilsen, Kirkham and Van Wijk (1959), Nixon and Lawless (1960) and Hewlett (1961) indicates that slow vertical percolation can provide an important supply of groundwater recharge during long dry periods after soil-moisture contents have declined below field capacity.

(3) That moisture fluxes into or out of the tension storages are independent of temperature, temperature gradients and vapour pressure gradients. Carey (1966) has shown that soil-moisture transport induced by thermal gradients and their associated vapour pressure gradients can be significant when compared with transport induced by hydraulic gradients, particularly when the temperatures or soil-moisture contents are low. Peck (1974) has provided a brief review of the theoretical and empirical evidence for the concept that the large observed increases in soil-moisture at below-freezing temperatures or under a snow cover are caused by upward migration of water. Abramova (1968) has presented evidence of extensive upward and downward transports of water as vapour in the relatively dry soils of the Precaspian Lowland in the U.S.S.R. The experiments demonstrating how Chinese elm could flourish with the soil in the root zone at wilting point were particularly interesting because they indicated that the required water was supplied by an upward transport of water vapour and that this was induced by a relative humidity gradient in the soil air rather than by a temperature gradient.

Plant Assumptions

The conventional conceptual techniques for estimating evapotranspiration are based on the assumption that the vegetation acts as a passive wick that transfers water from the tension storages to the atmosphere. This requires that leaf stomatal resistances be responsive only to internal leaf water controls and not to external environmental controls such as those imposed by irradiance, carbon dioxide in the ambient air, leaf temperature and humidity in the ambient air. Documentation for the existence of such controls and hence for the lack of reality in the assumption is presented in a detailed review by Cowan (1977) and in a shorter review by Hall, Schulze and Lange (1976).

The notion that the ambient humidity or the difference between the vapour pressure in the leaf and the vapour pressure in the air can have a

significant direct effect on stomatal resistance may seem strange to hydrologists and meteorologists. The indirect effects, whereby an increase in vapour pressure difference would increase transpiration which in turn would reduce internal leaf water content and thereby cause the stomata to contract, have long been recognized. Thus the indirect effects represent a feedback mechanism which reduces transpiration after leaf water contents have been reduced. In contrast, the direct effects represent a feedforward mechanism which reduces transpiration before leaf water contents have been reduced. Schultze et al. (1972) have shown that the direct effects of an increase in water vapour concentration difference (or vapour pressure deficit) on apricots growing in the Negev Desert is to reduce transpiration and increase leaf water content. Kaufmann (1979) provided evidence that the direct effects of an increase in the absolute humidity difference (or vapour pressure deficit) on four year old potted Engelmann spruce seedlings was to increase the stomatal resistance sufficiently to make the transpiration independent of the difference. The significance of such findings is that an increase in vapour pressure difference which produces an increase in potential evapotranspiration may cause an increase in stomatal resistance large enough to decrease the actual transpiration.

Much of the evidence for the direct effects of vapour pressure differences on stomatal resistance is based on instrumentation and techniques that are unfamiliar to hydrologists and meteorologists. However, Tan and Black (1976) have used Bowen-ratio energy balance measurements of evapotranspiration to estimate the daytime mean canopy resistance of a 10-m high Douglas-fir forest. Their results are shown in Fig. 1 and indicate that the canopy resistance increases more in response to increases in the daytime mean vapour pressure deficit (range approximately 8 to 20 mbars) than to decreases in daily soil water potential (range 0 to -10 bars) or in daily soil water content (range 23 to 8 percent by volume).

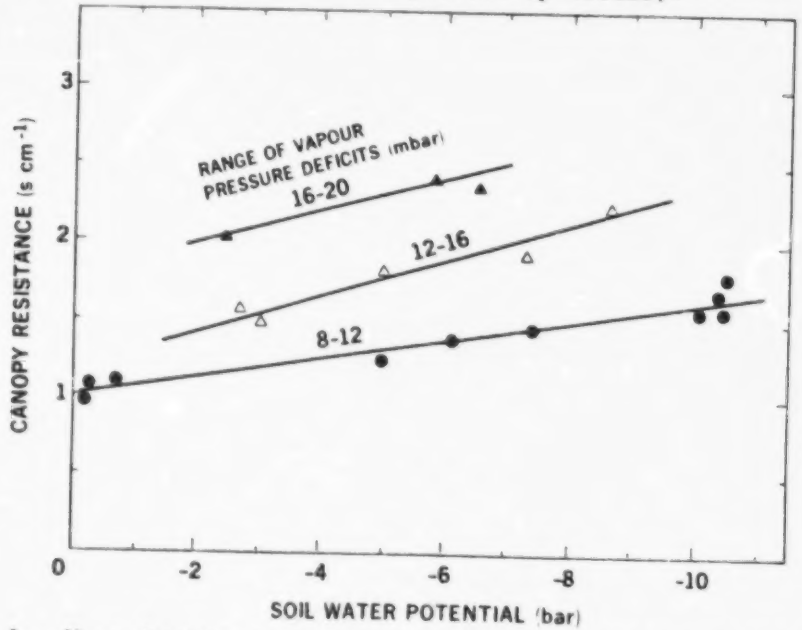

Figure 1. Mean daytime canopy resistance, soil water potential and vapour pressure deficit for Douglas Fir (Tan and Black, 1976).

The effects of ambient carbon dioxide concentrations on stomatal resistance have significance for current concerns about the hydrologic and climatic consequences of the combustion of fossil fuels. Based on their experiments with potted carnation plants, Enoch and Hurd (1979) have estimated that increases in carbon dioxide concentrations have decreased transpiration by 1.6 percent this century and could decrease transpiration by about 10 percent during the next 50 years. Such decreases could cause significant increases in runoff and a significant warming of the atmosphere which would augment the better known greenhouse effect.

Atmospheric Assumptions

The currently accepted conceptual techniques for estimating evapotranspiration, including that used in the SACRAMENTO WATERSHED MODELLING SYSTEM, are based on the assumption that pan evaporation or potential evapotranspiration are independent of the actual evapotranspiration and may therefore be used to reflect the evaporation demand. This assumption ignores the well known fact that a decrease in areal evapotranspiration caused by a reduction in the availability of water will increase the temperature and decrease the humidity of the overpassing air and that these in turn will increase pan evaporation or potential evapotranspiration.

Potential evapotranspiration is normally estimated from a solution of the energy balance equation and the vapour transfer equation. These equations can be solved with a graphical technique, an iterative technique or an approximate analytical technique. Kohler, Nordenson and Fox (1955) have shown that the approximate analytical solution developed by Penman (1948) can provide good estimates of evaporation from the Class A evaporation pan if modified to take into account both the difference between vegetated and water surfaces and the sensible heat flux through the wall and bottom of the pan. Therefore there are grounds for belief that the evaporation from any small water-filled container will provide a reasonable reflection of potential evapotranspiration, although the reflection will be somewhat distorted by differences in albedo, surface roughness and in the ratio of the latent heat transfer area to sensible heat transfer area.

According to the Penman (1948) equation the potential evapotranspiration increases when the vapour pressure deficit increases. This results from an increase in air temperature (as reflected in the saturation vapour pressure) and/or a decrease in humidity (as reflected in the dewpoint vapour pressure). Following the cause-and-effect chain beyond the customary first link, this is the kind of response that can be expected from the increase in heat flux and the decrease in vapour flux associated with a reduction in the availability of water for evapotranspiration from the surrounding area. The resultant feedback mechanism invalidates the currently accepted hydrometerological assumption that in any relationship between areal evapotranspiration and potential evapotranspiration the latter is the independent variable. Thus the use of potential evapotranspiration as a causal factor or forcing function is limited to two specific cases: (1) to existing moist areas so large that the effects of the evapotranspiration on the temperature and humidity of the overpassing air are fully developed and the areal evapotranspiration equals the potential evapotranspiration; and (2) to existing or hypothetical moist areas so small that the effects of the evapotranspiration on the temperature and humidity of the overpassing air are

negligible. Pans and other evaporimeters fit into the latter category insofar as size is concerned.

In Bernouilli's equation for open-channel flow, the potential energy responds negatively to changes in the kinetic energy. Thus there appear to be analogies between potential evapotranspiration and potential energy and between areal evapotranspiration and kinetic energy. To be completely analogous the relationship would have to be complementary, i.e. the responses would have to be both opposite in sign and equal, and both observational data and theory show that this is a distinct possibility. However it should be noted that the analogy can not be extended into the critical flow regime because areal evapotranspiration cannot exceed potential evapotranspiration.

The oasis effect is the best known phenomenon associated with the foregoing interactions. It can be demonstrated by comparing monthly evaporation from two U.S. Weather Bureau Class A Pans in the southeast desert basin of California during the years 1962, 1963 and 1964. Fig. 2 shows the pan evaporation in a large well-irrigated area at Indio U.S. Date Garden plotted against the pan evaporation in the desert at Death Valley for the last six months of the calendar year. The plotted regression line has a coefficient of correlation of 99 percent. The small zero-intercept can be attributed to the effect of the 2.7 degree difference in latitude in increasing the winter radiation inputs at Indio so that the slope represents the effects on pan evaporation of increasing the areal evapotranspiration from a near-zero value in the desert to a near-maximum value in an irrigated oasis. Thus Fig. 2 shows that the oasis pan evaporation is only 52 percent of the desert pan evaporation during the last six months of the calendar year.

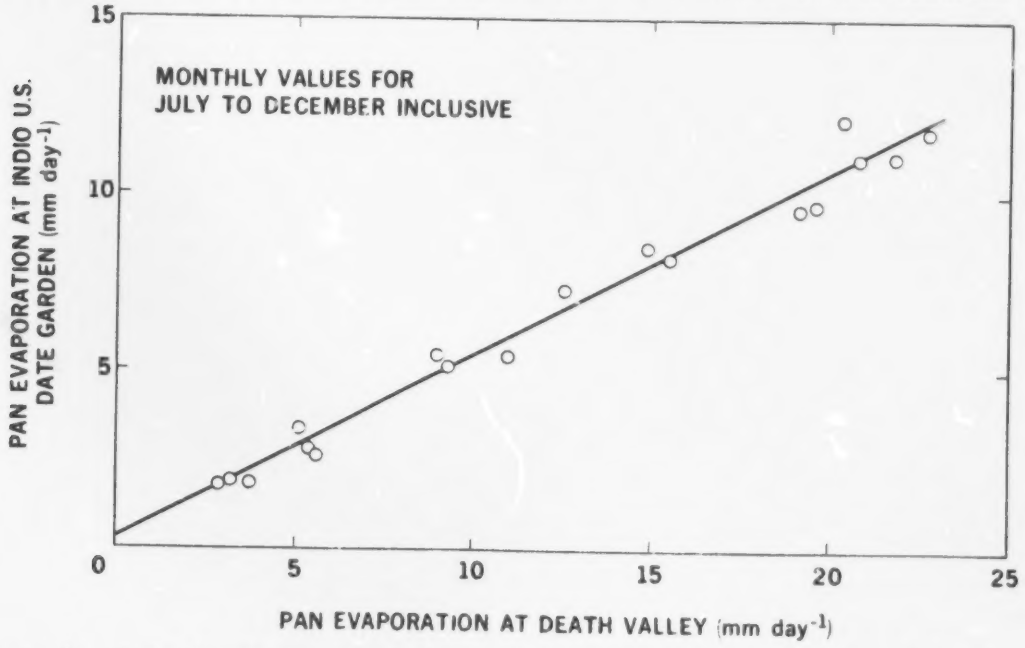

Figure 2. Relationship between Class A pan evaporation at Indio U.S. Date Garden and at Death Valley.

The oasis effect and the negative relationship between actual and potential evapotranspiration have been demonstrated by Davenport and Hudson (1967). They measured the variation in evaporation across a series of irrigated cotton and unirrigated fallow fields in the Sudan Gezira, using fiberglass dishes with black painted wells 113 mm in diameter and 36 mm in depth. The dish evaporation observations provided a somewhat distorted reflection of the potential evapotranspiration. The passage of air from the upwind desert (and/or the upwind unirrigated fallow fields) over the irrigated cotton caused the dish evaporation to decrease rapidly and approach a low constant value within 300 m - the width of the fields. Furthermore, as the air passed from irrigated cotton across unirrigated fallow the dish evaporation increased rapidly and approached a high constant value within 300 m. Fig. 3 shows the variation of dish evaporation across three irrigated fields on December 27, 1963. The description of the soil condition is presumably based on visual inspection and is related to the number of days since the last irrigation. Thus it is reasonable to assume that the actual evapotranspiration is greater in the "moist" field than in the "dry" field and that it is somewhere near its maximum possible value in the "wet" field.

At the upwind edge of the irrigated fields, where the dish evaporation decreases rapidly, the hot dry air from the desert (or the unirrigated fallow) loses heat and gains vapour from contact with the transpiring cotton leaves. Downwind from the transitional zone, where the dish evaporation approaches a low constant value, the effects of the evapotranspiration on the temperature and humidity of the overpassing air are well developed and approaching equilibrium. (Decreases in temperature and increases in humidity as the air moved across the irrigated cotton were observed over one field. The vapour pressure appeared to attain equilibrium values within 300 m but the temperatures were still decreasing, possibly because the observations were made above the level of the crop and dishes.) As it is only in an equilibrium zone that the term areal evapotranspiration has any meaning, the

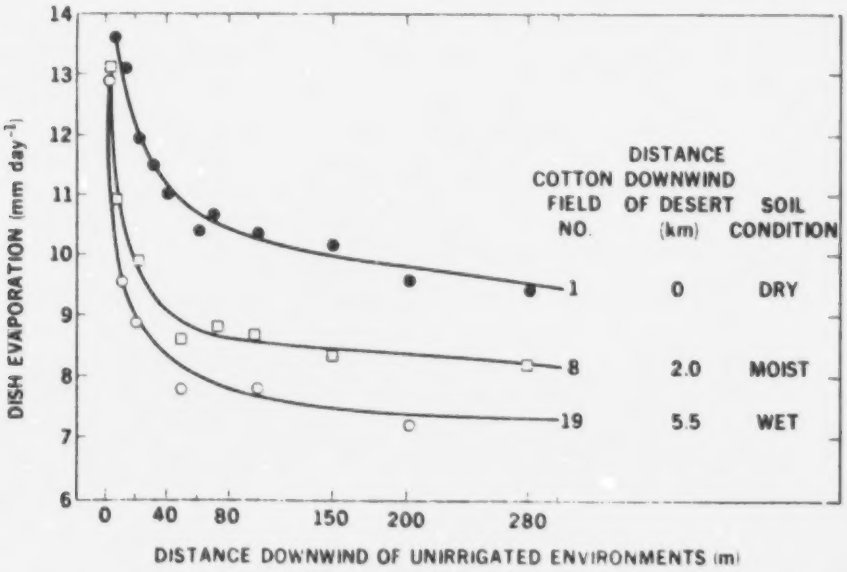

Figure 3. Comparison of evaporation rates across irrigated cotton fields on December 27, 1963 (Davenport and Hudson, 1967).

minimum size of an area for which the term is applicable is one in which the edge effects in the upwind transitional zone become insignificant.

The ratio of daily dish evaporation at the downwind edges of the individual irrigated cotton fields to that at the upwind edge of the irrigated area was 0.69 for the field with "dry" soil, 0.60 for the field with "moist" soil and 0.53 for the field with "wet" soil. This provides good evidence that the dish evaporation, and presumably the potential evapotranspiration, respond negatively to changes in areal evapotranspiration induced by changes in the availability of water.

Army and Ostle (1957) have inadvertently provided more direct evidence for the existence of a negative relationship between areal and potential evapotranspiration. They calculated actual areal evapotranspiration (E_T) from 0.1 acre plots of spring wheat by adding the total precipitation from seeding to harvest to the amount of soil moisture lost from seeding to harvest for 29 years at Huntley, Montana and for 26 years at Havre, Montana. The results were then related to the corresponding values of evaporation from nearby sunken B.P.I. tanks (E_{PW}), which provide a somewhat distorted reflection of potential evapotranspiration. The resultant regression equations for plots that were cropped every year were:

$$E_T \text{ (at Huntley)} = 30.8 - 1.025\ E_{PW} \qquad (1)$$

$$E_T \text{ (at Havre)} = 24.5 - 0.644\ E_{PW} \qquad (2)$$

and the regression equations for two plots that were cropped and left in fallow on alternate years were:

$$E_T \text{ (at Huntley)} = 34.6 - 1.142\ E_{PW} \qquad (3)$$

$$E_T \text{ (at Havre)} = 28.5 - 0.725\ E_{PW} \qquad (4)$$

The zero-intercepts for the four equations are in inches of water and the coefficients of correlation vary from 0.790 to 0.826 with a mean value of 0.814. In evaluating the results it should be noted that the tank evaporation would be higher than the potential evapotranspiration because of the low albedo of water and that this would cause the negative slopes to be underestimated; that unreported differences in vegetation and soil immediately adjacent to the various plots and tanks could account for some of the differences between the equations; and that unreported year-to-year variations of absorbed incident radiation would add to the scatter of the points and the uncertainty concerning the regression coefficients. With these considerations in mind the equations show that the relationship between actual evapotranspiration and potential evaporation is negative and that there is reasonable probability that it is complementary, i.e., that the slope is -1.

Summation

The foregoing evaluation shows that the assumptions used to estimate areal evapotranspiration in the conventional conceptual models are completely divorced from reality. They continue to be used because of their tractability and because of the ease with which unreal coefficients can be optimized when

the relevant variables are correlated, sometimes spuriously, through their pronouced seasonal patterns. This is evident in a discussion of Penman (1967) in which it is stated that "in terms of hydrology, one could be very wrong in the estimates of potential evaporation and still get the right answer if one had the right value of D" in which D is a poorly defined tension storage capacity which is usually obtained by optimization. The concealment of unrealistic assumptions by fudging tends to be ignored because the scientific and engineering literatures provide few if any examples of the consequences of practical applications or of the results of rigorous tests similar to those carried out by Garrick, Cunnane and Nash (1978).

Needless to say the foregoing conclusions apply also to other components of integrated basin response models. Some of the unreal assumptions have a direct bearing on other processes such as infiltration and groundwater recharge. However the main lesson to be learned is that seemingly plausible relationships can be not only approximate but diametrically opposed to reality. Thus there is a good chance that there are many more hidden interactions and feedback mechanisms in the hydrological cycle, any one of which would be capable of transforming model outputs to pretentious garbage. Under such circumstances the synthesis-oriented approach, with locally calibrated coefficients, must be seen as an attempt to make reality conform to the conventional wisdom and, in the case of the technique used for making evapotranspiration estimates in the SACREMENTO WATERSHED MODELLING SYSTEM, the conventional wisdom is twenty years out of date.

POTENTIALITIES OF ANALYTICAL APPROACH

General

The analytical approach to integrated basin response needs spatial averages for the major water balance components. The law of conservation of mass or the water balance requires that the precipitation be equal to the sum of the runoff, the evapotranspiration, and the change in storage. In the past is has been possible to routinely observe or estimate only two of these four quantities, i.e. the precipitation and runoff. The measurement of storage changes on a weekly, monthly, seasonal or even an annual basis is too expensive to contemplate, except in a research situation, because of the heterogeneity of topography, soils, vegetation and snow cover in most drainage basins. Therefore the water balance has been useful only to provide some idea of what happens over a period of many years when the change in storage becomes relatively insignificant and the evapotranspiration may be assumed equal to the precipitation less runoff. However the development of a technique which provides independent estimates of areal evapotranspiration from routine observations of temperature, humidity and sunshine duration (or global radiation) now permits detailed analysis of the relationship between integrated basin response and the changes in storage.

The basis for the complementary relationship between areal and potential evapotranspiration has been discussed in the preceding section. It permits the areal evapotranspiration, a product of complex processes and interactions in the soil-plant-atmosphere continuum, to be estimated by its effects on the routine climatological observations that are used to compute potential evapotranspiration. Because the technique avoids the complexities of the soil-plant system it requires no local optimization of coefficients and is,

therefore, falsifiable. This means that it can be tested rigorously so that errors in the associated assumptions and relationships can be detected and corrected by progresssive testing over an ever-widening range of environments. Such a methodology uses the entire world as a laboratory and requires that a correction made to obtain agreement between model and river basin water budget estimates in one environment must be applicable without modification in all other environments. The estimates resulting from the most recent application of this methodology agree closely with comparable long-term water budget estimates for 143 river basins in North America, Africa, Ireland, Australia and New Zealand.

The conceptual and empirical foundations of the complementary relationship, its use in providing the basis for operational estimates of areal evapotranspiration and lake evaporation, the testing of such estimates against comparable water budget values and the potential use of such estimates to provide the impetus for transforming hydrology from a descriptive to a predicting science are presented in a series of papers that have been submitted for publication. However the complementary relationship and its applications in a narrower range of environments have been published previously (Morton, 1978, 1979). Furthermore, documentation of the programs for the latest and as yet unpublished versions is available in FORTRAN language and in the Hewlett-Packard RPN notation (Morton, Goard and Piwowar, 1980).

Seasonal Water Balances

The simplest application of a water balance analysis is to provide explanations for differences in hydrological response between different basins. This is demonstrated in Fig. 4 with seasonal water balances for two rivers in Cameroon. Five years of data for the 355 km^2 basin of the Kallaio River have been published by Nouvelot (1973) and three years of data for the 86.5 km^2 basin at Station 7 in the Sanguéré have been published by Casenave (1978). The seasonal water balances are based on monthly values of observed precipitation, observed runoff and evapotranspiration estimated from the latest of the complementary relationship techniques which are averages for the 5-year and 3-year periods of record. The top solid line is the accumulated precipitation since the beginning of July; the middle long-dash line is the accumulated precipitation less evapotranspiration since the beginning of July; and the bottom short-dash line is the accumulated precipitation less evapotranspiration less runoff since the beginning of July. Thus the upper line represents a mass curve of precipitation, the vertical distances in the horizontally hatched area represent the ordinates of a mass curve of evapotranspiration, the vertical distances in the stippled area represent the ordinates of a mass curve of runoff and the vertical distances in the vertically hatched area represent the ordinates of a mass curve of storage change. The vertical distances on the right hand edge represent the annual totals for an average year. The very small annual totals for the storage change may represent an annual average of the storage change for the period of record or may represent the effects of errors in estimating or measuring the other components of the water balance. Note that the precipitation mass curves are flat during the long rainless season.

Fig. 4 contains an apparent hydrological anomaly. Although the two basins are separated by less than one and a half degrees of latitude and half

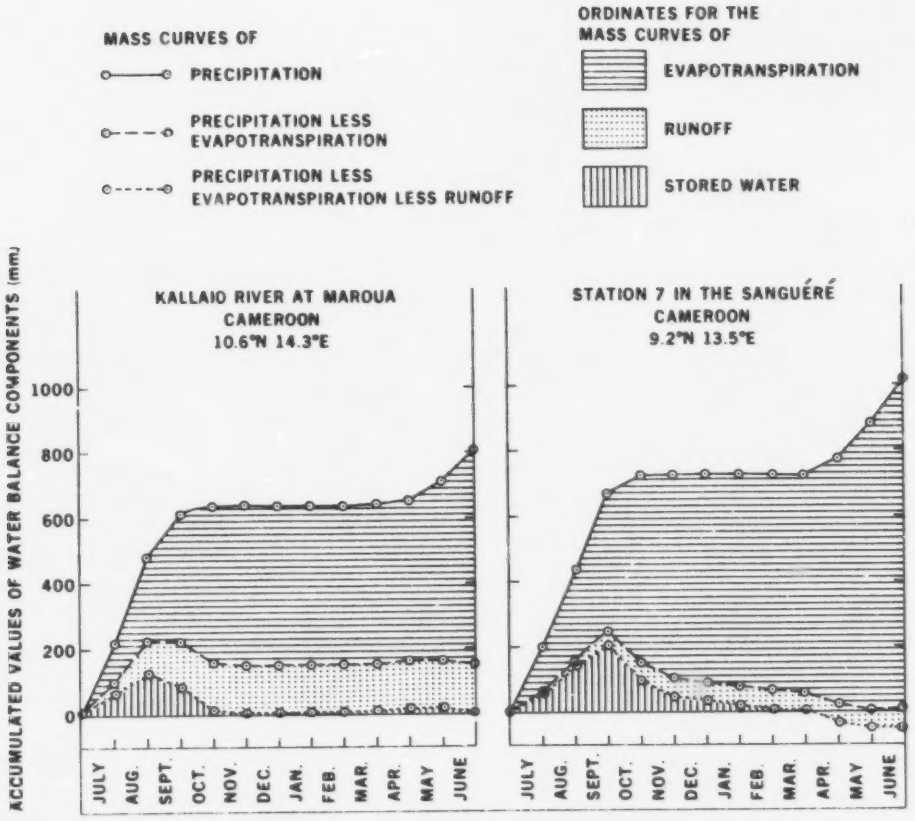

Figure 4. Seasonal water balances for two basins in Africa.

a degree of longitude, the runoff from the basin with the lower precipitation exceeds the runoff from the basin with the higher precipitation by approximately 150 percent. Until now this kind of anomaly could be explained only by assuming that there is groundwater runoff that flows out of the basin without being measured at the streamflow gauging site. Casenave (1978) studied the water balance of the Sanguéré basins using this assumption and concluded that the unmeasured groundwater outflow, which could be exploited without depleting the reserves, was approximately 15 percent of the precipitation and approximately 150 percent higher than the measured runoff from the basin at Station 7. However, with independent estimates and measurements of the principal water balance components, there is no need to make such an assumption. Thus Fig. 4 shows that the evapotranspiration from the Sanguéré basin is much higher than the evapotranspiration from the Kallaio basin and this difference explains why the higher precipitation produces a much lower runoff. According to this explanation the large exploitable groundwater resource does not exist.

The water balances indicate that the evapotranspiration from the Sanguéré basin exceeds the evapotranspiration from the Kallaio basin by 348 mm/year. This excess may include an error of 54 mm/year, the difference between the annual values of accumulated changes in basin storage, and does include the effects of the 206 mm/year difference in precipitation. The

remainder of 88 mm/year is attributable to the way that Sanguéré basin provides conditions favouring evapotranspiration at the expense of runoff in comparison with the Kallaio basin. In order of increasing plausibility the possible reasons for this difference are:

(1) The surface of the Sanguéré basin may be more pervious than the Kallaio basin so that more water infiltrates into soil moisture storage. This could account for the difference between the values of maximum storage accumulation but is not consistent with the low runoff from the Kallaio basin during the first three months of the wet season.

(2) The net radiation is higher for the Sanguéré basin than for the Kallaio basin and the increased availability of energy for evapotranspiration may have increased the availability of water for evapotranspiration.

(3) The water table in the Sanguéré basin may be close enough to the surface to supply water for significant soil evaporation during the long rainless season. However there is some doubt that the saturated zone would continue to supply water for evapotranspiration in excess of rainfall during the first three months of the wet season as shown in Fig. 4.

(4) Some vegetation in the Sanguéré basin may be deeper rooted than any vegetation in the Kallaio basin and may therefore draw water from greater depths. This is compatible with the tendency in Fig. 4 for the evapotranspiration from the Sanguéré basin to exceed rainfall during the dry season and the first three months of the wet season while the evapotranspiration from the Kallaio basin for the same period remains equal to the rainfall. Note that the change in storage from the end of October to the end of June for the Kallaio basin is negligible whereas for the Sanguéré basin it is approximately equal to the difference in annual evapotranspiration between the two basins less the difference in annual precipitation (i.e. 142 mm/year).

Real-Time Water Balances

The main reason for the analysis of real-time water balances is to find out what is actually happening in the basin to produce the integrated basin response. However the most obvious practical application is to forecasts of hydrological response and it is in these terms that the problem is discussed.

The only realistic basis for hydrological forecasts is an accurate estimate of the antecedent moisture or the amount of water stored in the soil, rock, snowpack, swamps and lakes of the basin at the beginning of the forecast period. The water stored in snowpacks can be estimated from snow surveys and the water stored in the lakes can be estimated from water level gauges but the financial and human resources required to monitor the water stored in the soil, rock and swamps of even a small basin are too horrendous to contemplate. However with independent estimates of areal evapotranspiration the water balance can be computed and the basin storage followed on a real-time basis. The basin storage is computed by selecting an arbitrary initial value and then accumulating the water balance estimates of storage change, i.e. precipitation (P) less runoff (Q) less areal evapotranspiration (E_T).

Fig. 5 has been prepared to demonstrate how the concept of basin storage can provide a basis for analysis and for forecasting in real-time. The data are for the basin of Perch Lake Inlets 4 and 5 near Chalk River, Ontario. The combined adjacent basins, with an area of only 0.37 km^2, have areas of forest, swamp and Precambrian rock outcrops but no lakes. The areal evapotranspiration was estimated from data at Petawawa Airport. The circular points in the upper half of Fig. 5 show the month-to-month variations in basin storage for an 8 year period. The vertical distances in the shaded area under the line joining these points represents the water stored in solid form in the snow cover as estimated from snow surveys, and the line under the shaded area represents the basin storage with the snow cover water content removed. The lack of any significant upward or downward trend over the 8 year period indicates that consistent errors in the precipitation, runoff or areal evapotranspiration are either very small or compensatory.

A major problem is that the basin storage (without the snow cover water content) includes tension storage in the unsaturated soil and gravity storage in the saturated groundwater zone and that each of these different types of storage has different effects on the runoff. Tension storage has an indirect influence on runoff through its effects on infiltration, overland flow and groundwater recharge. However, changes in tension storage produce no direct or immediate response in the runoff. On the other hand, the gravity storage has a direct influence on runoff. Thus, the runoff from a basin responds immediately to increases or decreases in the gravity storage. A graphical

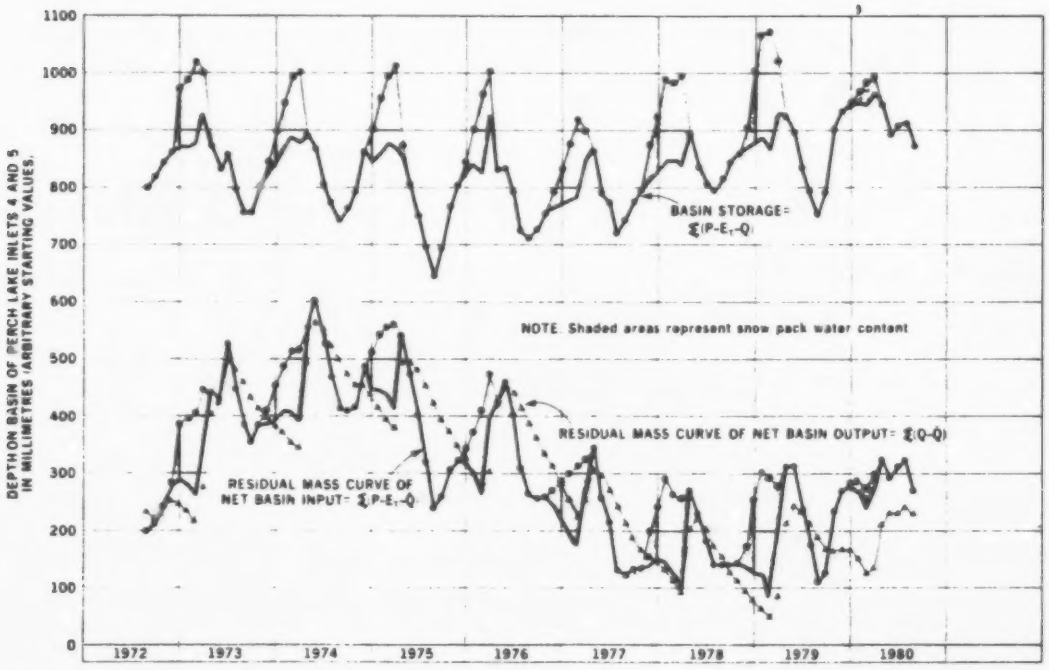

Figure 5. Basin storage and mass curves of input and output for combined basin of Perch Lake Inlets 4 and 5.

technique for analyzing these different effects has been presented by Klemes (1982) and is discussed briefly in subsequent paragraphs.

The circular points in the lower half of Fig. 5 are the accumulated values of precipitation (P) less evapotranspiration (E_T) less the long-term average runoff ($\overline{Q}$ = total runoff for 8 years divided by 96 periods) starting from an arbitrary initial value. The vertical distances in the shaded area under the line joining these points represents the water stored in the snow pack as estimated from snow surveys. Thus the line under the shaded area and through the circular points of the snow-free season represents a residual mass curve of the net liquid inputs to basin storage with respect to the long term average runoff. Similarily the line through the triangular points represents the mass curve of outputs from basin storage (Q = runoff) with respect to the long-term average runoff ($\overline{Q}$). The slopes of the mass curves represent the rates of net input or output with respect to $\overline{Q}$ and the differences between the mass curves of net input and output are the basin storage (without snowcover water content) to a datum specified by the difference in initial values. Note that the prime reason for including $\overline{Q}$ is to keep the mass curves horizontal over the 8 year period.

The relative positions of the net input and the output mass curves has been selected by trial-and-error to aid in discriminating between the responses of tension and gravity storage. Thus during most of the 8 years it can be noticed that:

(1) An increase in net input when the net input mass curve is above the output mass curve produces an increase in output because it tends to augment gravity storage.

(2) A decrease in net input when the net input mass curve is above the output mass curve has an insignificant effect on the output because it tends to deplete tension storage.

(3) A decrease in net input when the net input mass curve is below the output mass curve produces a decrease in output because it tends to deplete gravity storage.

(4) An increase in net input when the net input mass curve is below the output mass curve has an insignificant effect on the output because it tends to augment tension storage.

(5) As suggested by Klemes (1982) the difference between the initial values of the two mass curves is approximately equal to the average basin storage (without snow cover water content), as defined by the line in the upper half of Fig. 5, and the arbitrary initial starting point.

Tendencies (1) to (4) inclusive are masked to some extent by monthly averaging and by error in the components of the water balance. Moreover, tendency (2) is partially obscured during spring by evapotranspiration from gravity storage in the relatively large swampy area and tendency (4) is partially obscured by surface runoff from small saturated areas near the stream channels.

The kind of analysis presented in Fig. 5 has obvious applications. Thus

the amount by which the output mass curve exceeds the net input mass curve represents the amount of storage that must be replenished before the output (runoff) will respond in a significant way to increases in net input (precipitation less evapotranspiration) and the amount by which the input mass curve exceeds the output mass curve represents the amount of storage that must be depleted before the output will respond in a significant way to decreases in net input. Thus the distance between the two mass curves provides an excellent indicator of antecedent moisture which, when combined with average seasonal values of precipitation less evapotranspiration, can provide the basis for real-time forecasts. Applications of this potentiality would be more useful and informative if based on weekly time periods rather than monthly time periods. Shorter time periods are needed also in analytical studies where the objective is to learn more about the tension and gravity storages, their interactions and their effects on the integrated basin response. Such an analysis would be even more fruitful if combined with an analysis of another integrated basin response, the groundwater levels.

Errors and their Positive Aspects

The sensitivity of computed basin storage and mass curves to consistent minor errors in any one of the water balance components is the most serious hindrance to their use in hydrological forecasts or in analysis of integrated basin response. This is because the errors can accumulate to produce a trend that prevents realistic year-to-year comparisons. However, the potentialities are so great that the time and effort needed to solve the problem would be well worthwhile. The most obvious and expensive solution is to make an annual correction that is based on a concentrated late summer survey of the water stored in the soil, aquifers, lakes and swamps of the basin. Further investigations are required for more economic alternatives but at the present time the best approach seems to be graphical detection from anomalies in the mass curves of net input and output.

The sensitivity of computed basin storage to small consistent errors has positive aspects as well. Thus changes in the trend can be used to alert hydrometric or meteorological organizations to the development of possible errors or inconsistencies in their data and to detect the effects of changes in land use in the basin. This latter capability is demonstrated in Fig. 6 which shows changes in computed basin storage over a 14 year period for three rivers in the western outskirts of Toronto. The areal evapotranspiration estimates used in the computation of basin storage are the same for all three basins, being based on temperature and humidity observations at Toronto International Airport. The basin of the Humber River above Elder Mills is still largely rural and the absence of trend in the plot of basin storage demonstrates that the areal evapotranspiration estimated at Toronto International Airport was compatible with the law of conservation of mass throughout the 14 year period. The Mimico Creek and Etobicoke Creek basins were still largely rural in 1965 and 1966 although there was development for some distance upstream of the hydrometric stations. However during the 1970s the basin of Mimico Creek was transformed completely and the basin of Etobicoke Creek was transformed partially by urban development.

The basin storage for Mimico Creek has no trend prior to 1971. This indicates that the areal evapotranspiration estimated at Toronto International Airport was compatible with the water balance of the basin.

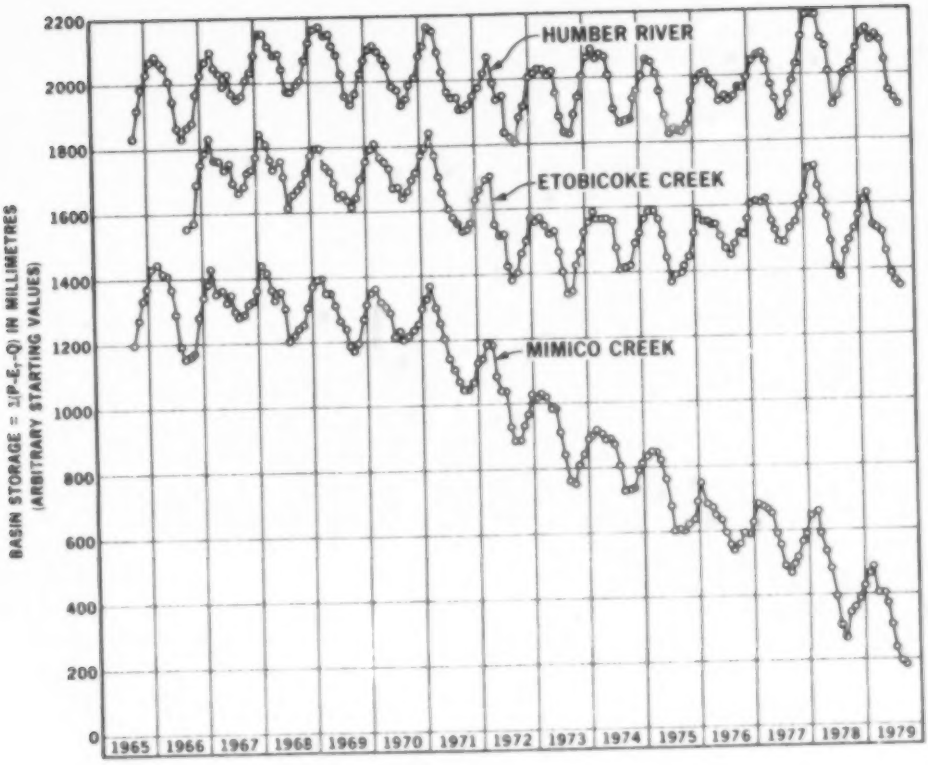

Figure 6. Basin storage for Humber River, Etobicoke Creek and Mimico Creek

After 1971, however, there was a strong negative trend in basin storage. The trend may have been due to consistent errors in the precipitation or runoff components of the water balance but this seems unlikely (the runoff would need to be almost 40 percent too high to account for the trend). A more probable explanation is that urbanization increased the runoff and decreased the evapotranspiration without affecting the evapotranspiration estimated at Toronto International Airport. An undetected reduction in evapotranspiration of approximately 20 percent could account for the trend and this compares with a difference of 15 percent between the evapotranspiration for a rural area estimated at Edmonton International Airport and the evapotranspiration for an urban area estimated at Edmonton Industrial Airport.

The trace of basin storage for Etobicoke Creek in Fig. 6 is more difficult to explain. Thus the trend remained horizontal until 1970-71 and then started a downward trend similar to that for Mimico Creek. Unlike Mimico Creek, however, the trend became horizontal again in 1972-73. This means that there were two lengthy periods with balanced water balances separated by a two-year transition period. If the transition was real, i.e. if it was not caused by an error in the precipitation or runoff values that was later corrected, it may have been due to some permanent reduction in stored water associated with urban pressures, such as the drainage of large swamps or the lowering of the water table. As the decrease in basin storage was approximately 200 millimetres the volume permanently abstracted from storage would have been about 40 million cubic metres.

The trace of basin storage for the Castor River near Ottawa, Ontario, is not shown. It has a similar appearance to that for Mimico Creek in that a strong negative trend developed after about five years with no trend. There is a good chance that the negative trend after 1972 was due to a change in land use in the basin from pasture and hay production to corn cultivation with tile drainage. However, the development of error in the evapotranspiration estimates cannot be ruled out as the humidity inputs during the period of negative trend appear to be too high.

Summation

One of the major problems in hydrology has been the apparent intractability of the analytical approach to integrated basin response. This has caused education and research in hydrology to be focused on the easier peripheral problems so that most engineers and hydrologists, including the author, have found it difficult to visualize the liberating effect that the removal of this constraint can have. The examples presented herein provide some indication of how the ability to analyze integrated basin response could be a major factor in overcoming the current sterility of hydrologic research and practice and in providing the knowledge needed to transform hydrology from a descriptive to a predictive science.

CONCLUDING DISCUSSION

The synthesis-oriented approach to integrated basin response is founded on the supposition that most hydrological processes and interactions are well understood - a supposition that is based more on hope that on fact. Thus a critical examination of the seemingly plausible and straightforward assumptions underlying the conventional conceptual techniques for estimating evapotranspiration has shown that they are completely divorced from reality, mostly because of little known or studiously avoided feedback mechanisms. Furthermore there is every probability that there are many other hidden interactions and feedback mechanisms that relate to other components of the hydrological cycle. If this is the case, the synthesis-oriented approach with locally calibrated coefficients cannot be taken seriously since it is merely an attempt to make reality conform to the conventional wisdom.

Water planning and management require models of integrated basin response. Those developed for simple simulation and for real-time forecasting can be made more realistic without massive infusions of new knowledge. However this requires that:

(1) Each assumption be identified and evaluated by a survey of all relevant literature, similar to that presented herein. If one is found to be unrealistic it may be necessary to replace it by another assumption. However the new assumption must be compatible with all available knowledge. In selecting new assumptions, the slightest hint of reality should be given more weight than mathematical tractability. Thus a crude approximation is much superior to a polished mathematical formulation that is diametrically opposed to reality.

(2) Model results be evaluated by some objective criteria, such as those suggested by Garrick, Cunnane and Nash (1978). For the simulation mode they advocated comparison with the mean flow for each calendar day as

computed from data observed during the calibration period. For the forecasting mode they recommended that this standard of comparison be modified to include a simple statistical updating procedure that is based on the deviations of the daily flows during the calibration period from the mean flows for each calendar day. Furthermore, they demonstrated that these seemingly relaxed standards of comparison provided better results for the Sanaga Basin in both the simulation and the forecasting modes than the model that produced the best results for the same basin in the W.M.O. (1975) intercomparison project.

Models of integrated basin response for the purposes of simulation or real-time forecasting may be justified if the foregoing steps are taken. However, there is no justification whatsoever for models of integrated basin response that purport to predict the effects of land use or climatic changes. This is because the methods used for estimating evapotranspiration, the component of the hydrological cycle most directly affected by such changes, are so crude. (The complementary relationship cannot be used either because the estimates are based on effects rather than causes.) Particularly unrealistic are the many recent attempts to predict the hydrological effects of climatic change with conventional models of integrated basin response as exemplified in the SACREMENTO WATERSHED MODELLING SYSTEM. Not only are these attempts based on assumptions that are diametrically opposed to reality, as demonstrated in a previous section, but they ignore the fact that changes in the atmospheric constituent presumably responsible for the climatic change, i.e. carbon dioxide, also change the stomatal openings of the plants and thereby have a direct effect on evapotranspiration.

The cast of mind induced by the synthesis-oriented approach can have a detrimental effect on research into hydrological processes. The current work on stomatal resistance, which is based on an analogy to Ohm's law, could be a case in point. The analogy may be valid but its unquestioned use when Schultze et al. (1972) have provided evidence to indicate that an increase in vapour pressure deficit (analagous to the voltage) can cause a decrease in transpiration (analagous to current) gives the appearance of forcing reality to conform to an assumption. If so, the analogy is having a detrimental effect on hydrology by hindering the formulation of alternative conceptual frameworks.

Laboratory research and plot research have value in the study of integrated basin response. Thus much of the information used in the critical review presented previously was derived from such research. Furthermore, the relationships thus derived may be useful in models of integrated basin response if it is accepted that a crude approximation to reality is preferable to an untested assumption. Since most laboratory and plot studies are carried out by researchers who are unfamiliar with the conceptual, methodological and instrumental limitations of basin hydrology, it may be possible to increase the relevance of the results with more input from basin researchers and modellers during the planning stages.

Although the results of laboratory and plot studies may be very helpful, the only way to learn more about integrated basin response is to analyze it. The examples presented herein demonstrate that such analysis can be used not only to learn more about the processes and interactions that produce the integrated basin response but also to provide the solutions to immediate

practical problems. It should be noted however that successful application of the analytical approach must be based on a realization that the conventional wisdom can be wrong; that very little is known about hydrological processes; that the hydrological cycle is riddled with paradoxical feedback mechanisms; and that a crude approximation to reality is superior to an assumption selected solely for its mathematical tractability.

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RIVER FLOW FORECASTING USING FILTER MODELS

by

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INTRODUCTION

Much attention has been given to the problem of forecasting river flows, one or more time periods ahead. Techniques based on existing and expected meteorological conditions, past behavior of the river basin, the physical condition of the soil, and the historical correlation structure between flows from different time periods, have all been used with varying degrees of success.

To use any of the available models to forecast flow it is necessary to estimate the values of the model parameters and coefficients. This may be done off-line prior to the forecasting process, but doing so assumes that the process is static or time-invariant. To allow for changes in the parameter values and model structure as the forecast evolves, the parameters and model can be estimated and updated at each time period.

When discussing methods of updating or forecasting it is convenient to use the notation of state-space models. State-space models of random processes are based on the assumption that the state of a process contains the information from the past that is necessary to forecast the future. In reality, it is only practical to deal with states of finite dimension. The state-space approach, therefore, consists of a dynamic model which describes the state of the system over time, subject to modelling errors, and a measurement equation which

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provides noisy estimates of some of the states of the system (Wood, 1980).

There are many techniques available to update the state of a system using information gained from measurements taken of some of the states of the system. The most powerful of these methods is probably the Kalman filter, but others exist (e.g. Ganendra, 1980; Cluckie et al, 1980; Wood and Szollosi-Nagy, 1978).

The Kalman Filter

The process of filtering has been described as a mathematical operation which utilizes past data or measurements of a dynamic system in order to make more accurate statements about the present, future, or past state of the system than could have been made using information from a single direct measurement (Kalman, 1978).

Some of the earliest work on state estimation was done by Kolmogorov (1941) for prediction using discrete time intervals and by Wiener (1942) in continuous time. The work of both Kolmogorov and Wiener was concerned with predicting stationary stochastic processes. Kalman (1960) removed the requirement of stationarity so that it was no longer necessary to have an infinite length of data (Schmidtke, 1980). The resulting technique, which employs aa computer-oriented algorithm, is commonly referred to as the Kalman filter.

The Kalman filter formulation consists of a system model which, following the notation of Todini (1978), is given as

$$X_t = \phi_{t-1} X_{t-1} + \Gamma_{t-1} W_{t-1} \tag{1}$$

and a measurement model given as

$$Z_t = H_t X_t + V_t \tag{2}$$

where X_t = the (n x 1) state vector,

Z_t = the (m x 1) measurement vector,

ϕ_{t-1} = the (n x n) matrix of parameters forming the state transition matrix

Γ_{t-1}, H_t^T = scaling matrices of compatible dimension (n x m),

and V_t, W_t are Gaussian, independent processes with

$$E[W_t] = \bar{W},\ E[V_t] = \bar{V}$$

$$E[(W_t-\bar{W})(W_k-\bar{W})^T] = Q\ \delta_{tk}$$

$$E[(V_t-\bar{V})(V_k-\bar{V})^T] = R\ \delta_{tk}$$

$$E[(W_t-\bar{W})(V_k-\bar{V})^T] = 0\ \forall\ t,k$$

where $E[\cdot]$ denotes the mathematical expectation and δ_{tk} is the Kroneker delta defined as

$\delta_{tk} = 1$ if $t = k$

$\delta_{tk} = 0$ if $t \neq k$

If ϕ_{t-1}, H_t, Γ_{t-1}, $\bar{W}$, $\bar{V}$, Q and R are all known, then the optimal estimation of the state vector, X_t, can be performed by the algorithm given as (21)

$$\nu_t = Z_t - H_t\ \hat{X}_{t/t-1} - \bar{V} \tag{3}$$

$$K_t = P_{t/t-1}\ H_t^T\ (H_t P_{t/t-1}\ H_t^T + R)^{-1} \tag{4}$$

$$\hat{X}_{t/t} = \hat{X}_{t/t-1} + K_t \nu_t \tag{5}$$

$$P_{t/t} = (I - K_t H_t) P_{t/t-1} \tag{6}$$

$$\hat{X}_{t+1/t} = \phi_t \hat{X}_{t/t} + \Gamma_t \bar{W} \tag{7}$$

$$P_{t+1/t} = \phi_t P_{t/t} \phi_t^T + \Gamma_t Q \Gamma_t^T \quad (8)$$

where ν_t = the innovation of the filter,

K_t = the Kalman filter gain,

$\hat{X}_{t/t}$ = the updated state estimate,

$P_{t/t}$ = the updated error covariance matrix,

$\hat{X}_{t+1/t}$ = the extrapolated state estimate,

$P_{t+1/t}$ = the extrapolated error covariance matrix,

I = the identity matrix.

When applying Kalman filters to hydrologic systems, several difficulties have been encountered (after Wood, 1980). In order to use the Kalman filter, the probabilistic properties of the state model must be known. It is therefore necessary to determine both the system error covariance matrix, Q, and the measurement error covariance matrix, R. As well, the Kalman filter algorithm requires, as an initial condition, an unbiased estimate of the state vector at time t = 0, X_0, and the error covariance matrix of this estimate, P_0. The algorithm further assumes that the matrix of model parameters, ϕ, is perfectly known. Since in reality, the above quantities are poorly known at best, techniques must be explored to provide adequate estimates of Q, R, X_0, P_0, and ϕ and to minimize the effects of errors in these estimates.

Good estimates of the system and measurement noise are essential if an optimal estimate of the state vector is to be provided by the Kalman filter. If the measurement noise is too much larger than the system noise, less weight will be given to any new data measurements in the updating of the state vector. This can lead to filter divergence. Alternatively, if the system noise is too large, relative to the measurement noise, the filtered estimates will follow the

measurements closely such that the filtered and measured estimates are essentially the same (Lettenmaier and Burges, 1976).

If, as is usually the case, the relative magnitudes of the noise terms are not accurately known, it is possible to recursively estimate them under certain conditions. The effect of imperfect initial estimates of the system state can also be minimized by starting the estimation procedure well in advance of the initial period for which forecasts are required. This allows the filter to become "tuned" so that initial, perhaps poor, estimates of the state have an opportunity to be damped out.

The condition which must be met to allow the recursive estimation of the unknown statistics, $\bar{W}$, $\bar{V}$, Q, and R, is that every element of the state vector which is estimated must also be measured (Todini and O'Connell, 1977). If the above condition is met, then the innovation sequence can be assumed to be a Gaussian independent process with

$$E[\nu_t] = 0 \tag{9}$$

$$E[\nu_t \nu_t^T] = H_t P_{t/t-1} H_t^T + R = C_{o,t} \tag{10}$$

$$E[\nu_t \nu_{t-k}^T] = 0 \qquad t \neq k \tag{11}$$

The above three equations are the necessary conditions to assure that the filter is a minimum variance estimator. The unknown statistics can be estimated by applying Equations (9) through (11) to the Kalman filter algorithm. From Equation (9) and Equation (3) it is possible to estimate $\bar{V}$ as

$$\hat{\bar{V}}_t = \frac{t-1}{t} \hat{\bar{V}}_{t-1} + \frac{1}{t} (Z_t - H_t \hat{X}_{t/t-1}) \tag{12}$$

where $\hat{\bar{V}}_t$ = the estimate of the quantity $\bar{V}$.

Applying Equation (10) results in

$$\hat{R}_t = \hat{C}_{0,t} - H_t P_{t/t-1} H_t^T \tag{13}$$

where

$$\hat{C}_{0,t} = \frac{t-1}{t} \hat{C}_{0,t-1} + \frac{1}{t} (\nu_t \nu_t^T) \tag{14}$$

Equations (14) and (15) can be combined and written in recursive form as

$$\hat{R}_t = \frac{t-1}{t} \hat{R}_{t-1} + \frac{1}{t} (\nu_t \nu_t^T - H_t P_{t/t-1} H_t^T) \tag{15}$$

The remaining two statistics can be estimated by utilizing Equations (9) through (11) and imposing the condition that the filter provides an unbiased estimate if the state vector. The resulting estimates are

$$\hat{\bar{W}}_{t+1/t} = \hat{\bar{W}}_{t/t-1} + \frac{1}{t} (\Gamma_t^T \Gamma_t)^{-1} \Gamma_t^T K_t \nu_t \tag{16}$$

and

$$\hat{Q}_{t/t} = \frac{t-1}{t} \hat{Q}_{t-1/t-1} + \frac{1}{t} (K_t \nu_t \nu_t^T K_t^T + P_{t/t} - \phi_{t-1} P_{t-1/t-1} \phi_{t-1}^T) \tag{17}$$

For a complete derivation of the above statistics the reader is referred to the work of Todini and O'Connell (1977), Todini et al (1976), and Wood and Szollosi-Nagy (1978).

By using the algorithm presented in Equations (3) through (8) and the estimates of the statistics $\bar{V}$, $\bar{W}$, Q and R obtained from Equations (12), (16), (17) and (14) respectively, it is possible to obtain optimal estimates of the state vector provided that the parameter matrix, ϕ, is known. Methods available for estimating the value of model parameters are discussed below.

Techniques for estimating model parameters can be categorized as either off-line or on-line methods. Off-line parameter estimation refers to those techniques which do not process data as it becomes available but rather use a set of data which was collected prior to the model utilization stage (Wood, 1980). The major drawback to using off-line techniques to estimate parameters is that the model structure must be known in advance and the parameters must be assumed to be time-invariant. If these assumptions are too restrictive, parameter estimation can be performed on-line.

There is an on-line formulation of the ordinary least squares approach which is called recursive least squares (Cluckie et al, 1980). Problems arise when attempting to use ordinary least squares techniques due to the state vector, X_t, not being perfectly known. Since the state vector must be estimated from noisy measurements, ordinary least squares results in inconsistent estimates of the parameters (Kendall and Stuart, 1967). It has been shown by Todini and O'Connell (1977) that when an ordinary least squares algorithm is used, whether recursive or otherwise, the parameters will be underestimated.

To avoid the problem of a noise-corrupted state vector, it is possible to utilize a vector which is correlated with the state vector but not with the measurement noise, in order to estimate the parameter values. A methodology which incorporates this approach is called the Instrumental Variables (IV) technique. This method uses an additional variable, termed the Instrumental Variable, which is correlated with the "true" value of the state vector but not with the measurement noise. This variable, which can be obtained by filtering the state vector estimate, can be used to provide a consistent estimate of unknown parameters using a least squares estimator (Todini and O'Connell, 1977).

Expanding the state vector of the system model by the addition of the model parameters, the resulting filter is referred to as an extended Kalman filter. Including the parameters in the state vector results in a nonlinear state equation. For the solution of the extended Kalman filter it is necessary to replace the resulting nonlinear model with a linear model and it is also necessary to replace the resulting non-Gaussian distributions with Gaussian distributions (Schmidtke, 1980).

A method of parameter estimation, which is similar to the Instrumental Variables technique is the mutually interactive state/parameter estimation (MISP) technique (Todini and O'Connell, 1977). The MISP method was derived using the optimality properties of the Kalman filter, namely, the innovation sequence is a zero mean white-noise process and the updated state vector is independent of the filter innovation. The technique involves using two filters, one in the state-space and one in the parameter-space. The two filters are used recursively each time step with information from each filter being used in the optimal estimation performed by the other filter.

EXAMPLE APPLICATION

The Sturgeon River basin is located in the Canadian shield region of northern Ontario. The Sturgeon River drains an area of approximately 7000 square kilometers (McBean et al., 1981) and is the largest tributary of Lake Nipissing, as can be seen in Figure 1. The basin consists of scattered settled areas which include many rural and recreation-oriented hamlets. The greater portion of the watershed is uninhabited with many areas remaining as Crown Land and unorganized territories.

Specific to water resources concerns, serious flooding has been reported on the Sturgeon River in 1947, 1960, and 1979. The community of Field,

which was most seriously affected by the floods of 1979, has experienced significant monetary loss on ten occasions since 1922 (MacLaren, 1980). Flooding on the Sturgeon River has occurred almost exclusively during the spring freshet and has been a result of the combined effects of precipitation and snowmelt. A real-time forecasting procedure developed for the basin would enable action to be taken to minimize the damages due to high flows on the Sturgeon River.

The Martinec snowmelt model is an index model capable of predicting potential runoff generated by snowmelt while requiring only a temperature index derived from averaging daily maximum and minimum temperatures. To reflect snowmelt, the state vector to be used for river flow forecasting must therefore include a temperature index. The state vector must also include precipitation terms in order to model the rainfall-runoff process. The final elements to be included in the state vector are flow terms; the flow at the present time step must be included since it is the quantity which is being forecast. It has been suggested (Wood and Szollosi-Nagy, 1978) that past flow values can also be useful in state vectors used to model the runoff process. Past flow terms are useful for modelling the recession portion of a hydrograph and also for modelling baseflow conditions. The state vector is therefore

$$X_t = [q_t, q_{t-1}, \ldots q_{t-k}, P_t, P_{t-1}, \ldots P_{t-m}, T_t, T_{t-1}, \ldots T_{t-\ell}]^T \qquad (19)$$

where q_t = the flow at time t,

P_t = the rainfall at time t,

T_t = the value of the temperature index at time t.

Values of k, m, and ℓ, the number of flow, precipitation, and temperature terms to be included in the state vector, are estimated from historical data for the river basin.

In the formulation of the state model of a hydrologic system, not all of the elements of the parameter matrix are unknown. It is, therefore, convenient to represent the unknown parameters by θ_t, a (pxl) vector. There are two approaches to modelling the variations of the parameter vector: i) assume that the parameters are time-invariant, but unknown, and ii) assume the parameter vector can be modelled with a "random walk" model.

i) When the parameters are assumed to be time-invariant, the parameter filter will essentially be trying to estimate the optimal value of a quantity which could be changing with time. The estimated parameter values should then converge to the actual, but changing, parameter values (i.e., the filter will be tracking a moving target).

ii) Modelling the temporal variation of the parameter vector with a "random walk" model was successfully used by Wood and Szollosi-Nagy (1978). This approach allows for parameter variations with time due to changing physiographic characteristics of the basin.

The second approach is used below. The MISP algorithm presented here is based on the work of Todini and O'Connell (1977) and Todini (1978). The state update equation is used as a basis for the derivation of the Kalman filter for the estimation of the parameter vector. The resulting algorithm is given as

$$\nu_t^* = H_t K_t \nu_t \tag{20}$$

$$R^* = H_t K_t C_O K_t^T H_t^T \tag{21}$$

$$K_t^* = P_{t/t-1}^* H_t^{*T} (H_t^* P_{t/t-1}^* H_t^{*T} + R^*)^{-1} \tag{22}$$

$$\hat{\theta}_{t/t} = \hat{\theta}_{t/t-1} + K_t^* \nu_t^* \tag{23}$$

$$P^*_{t/t} = (I - K^*_t H^*_t)\, P^*_{t/t-1} \tag{24}$$

$$\hat{\theta}_{t+1/t} = \hat{\theta}_{t/t} + \Gamma^*_t \bar{W}^* \tag{25}$$

$$P^*_{t+1/t} = P^*_{t/t} + \Gamma^*_t Q^* \Gamma^{*T}_t \tag{26}$$

where all the symbols are as defined for the state-space Kalman filter with asterisks (*) used to denote an element of the parameter space filter. The exchange of information between the state filter and the parameter filter is illustrated in Figure 2.

Forecast Results

The forecasting results obtained using the model were generally quite satisfactory. Figure 3 shows the forecasted and measured flows for 1967 as well as the 95% confidence limits for the forecasted flows. These results are indicative of a much larger set contained in Burn (1982). Figure 3 reveals that the measured flow values are always within the 95% confidence limits of the forecasted flows indicating that the one day ahead forecasts given by the Kalman filter are providing reliable estimates of the actual river flow. The confidence limits plotted in Figure 3 can be seen to decrease in size with increasing time. This increased confidence with time in the forecast values is a reflection of the "learning" process of the filter. As the estimation procedure advances in time, the system model and its parameters become known more exactly which allows a greater confidence to be placed on the forecast values.

The parameter space filter provides filtered estimates of the unknown parameter values at every time step. It is noted that for a given year the 95% confidence limits become narrower with increasing time, reflecting the increased certainty of the estimated values of the parameters as time passes. This

increased certainty is a result of an increase in the knowledge of the system model which has been obtained as a result of estimating and measuring the river flow for many time steps. The two flow parameters remained relatively constant over the forecast period indicating that the relationship between present flow and past flow values is basically unchanged over the time-frame of observation.

Comparisons with Stochastic Model

In order to evaluate the results of forecasting the Sturgeon River flow utilizing a Kalman filter technique, an alternate forecasting method was employed to illustrate the potential improvement in forecasting beyond a conventional model. The method chosen as a basis for comparison is a stochastic forecasting model using previous values of measured flow. Historical (1958) flow data for the Sturgeon River was used to identify the optimal autoregressive model to be used for the forecasting. The model identification process was performed using the techniques of (1). The stochastic model chosen to be used to compare with the Kalman filter model was a lag-two Markov model. A lag-two model implies that the flow at the present time step can be predicted knowing the values of the flow for the two previous time steps.

In order to quantify the relative merit of the two forecasting techniques, it is necessary to determine appropriate mathematical means of measuring the effectivenss of each method. The forecast results were evaluated based on their i) mean squared error, and ii) forecast of peak flow, as described below.

i) The mean squared error (MSE) of the forecast results was calculated by first squaring the difference between the measured and forecasted values. The squared values were then summed over all the forecasts for a given year

and divided by the number of values forecasted. The MSE places a heavier penalty on forecasts which differ from the measured value by a large amount as evidenced by the squaring of the difference between the measured and forecasted values.

ii) The peak flow forecasting capability of the two models was measured by calculating the difference between the measured and actual peak flow and dividing this difference by the measured peak flow. The resulting quantity, multiplied by 100, is the percent error in forecasting the peak flow. This calculation was performed for each local maxima when the seasonal hydrograph contained more than one peak value. The error in predicting the peak flow is a useful means of determining the utility of the forecasting model for providing early warning of potential flood events.

The calculated mean squared error for both models and each of the forecast years is given in Table 1. The results for the percent error in forecasting the peak flow are shown in Table 2.

The Kalman filter model is observed to have a lower MSE than the Markov model for every year except 1964. The forecasting results for 1964, using the Kalman filter model, were generally poorer than the results using the Kalman filter for the other years. There were several significant outliers in the forecast results for 1964 which probably contributed a substantial portion of the total MSE. This would explain the high mean square error noted for the Kalman filter model, relative to the MSE for the Markov model for 1964. The average MSE for the Kalman filter model is about 20% less than the average MSE for the Markov model indicating that the Kalman filter model represents a significant improvement in forecasting ability over the Markov model.

TABLE 1

Mean Square Forecast Error

YEAR	KALMAN FILTER	LAG 2 MARKOV
1954	1.15	1.34
1957	0.68	1.14
1964	1.45	0.81
1967	0.98	1.32
1968	0.18	0.33
1970	1.78	2.47
AVERAGE	1.04	1.24

TABLE 2

Percent Error in Prediction of Peak Flow

YEAR	KALMAN FILTER	LAG 2 MARKOV
1954	13.7	32.6
	12.9	11.4
1957	14.4	12.7
1964	11.6	47.4
1967	7.9	17.0
	11.2	11.7
	19.3	11.4
1968	2.2	34.7
	5.3	12.6
	10.7	21.4
1970	18.3	28.2
	3.1	16.9
AVERAGE	10.9	21.5

The Kalman filter model is generally capable of predicting the peak flow with less error than the Markov model, although the Markov model does forecast the peak flow with marginally smaller error in some instances. There is a considerable range of observed errors in forecasting the peak flow. The Kalman filter produced errors in the range of 2 to 19 percent while the Markov model exhibited errors ranging from 11 to 47 percent. The average error of almost 11 percent for the Kalman filter model is roughly one-half of the average error in predicting the peak for the Markov model, which was approximately 22 percent. It is therefore evident that the Kalman filter model is a superior technique for predicting peak flows for this application.

The rather noticeable superiority of the Kalman filter model could perhaps have been expected. The Markov model, since it uses only flow data, has no means of anticipating rises in flow since it does not utilize any data related to the flow generation mechanisms, such as rainfall or snowmelt data. Therefore the model's forecasts are based only on past measurements of flow data. This explains the satisfactory performance of the Markov model for predicting the baseflow portion of the hydrograph (where there are no exogenous inputs), and the poor performance on the rising limb of the hydrograph.

The Kalman filter model has the further advantage of having the model parameters recursively updated. This allows the model to simulate the effects of changing physiographic characteristics of the river basin on river flow. While the parameters were not found to change rapidly, there were still definite changes in some of the parameter values which must be reflected by the model in order to properly forecast river flow. Also, the fact that the state vector is updated when the Kalman filter is used, allows for errors in measuring the input data. The Markov model, by comparison, assumes that the input values are perfectly known.

CONCLUSIONS AND RECOMMENDATIONS

The potential utility of incorporating Kalman filtering techniques into a forecasting scheme in order to reflect uncertainties present in the data measurements and in the system model employed, is substantial. The forecasting methodology presented was observed to provide satisfactory forecasts of the one day ahead river flow resulting from rainfall and snowpack dissipation during the spring freshet period.

An examination of the forecast results reveals the adaptability of the Kalman filter model to the particular application. This "learning" process is evidenced both through a decrease in the confidence limits of the forecasts as the season progresses and an increase in the certainty with which the model parameters are known, as reflected by a decrease in the confidence limits of the estimates of the parameter values. The adaptability of the model further allows it to reflect changes occurring within the river basin during the spring freshet period.

While the potential for utilizing Kalman filtering techniques for forecasting with actual data has been demonstrated, further work should be done to quantify physically-based methods for determining initial estimates of the covariance matrices of the parameter filter. Although the methodologies employed herein gave satisfactory results, a method based on physical characteristics of the flow generation process would ensure that reliable results could be obtained when applying the technique to other basins.

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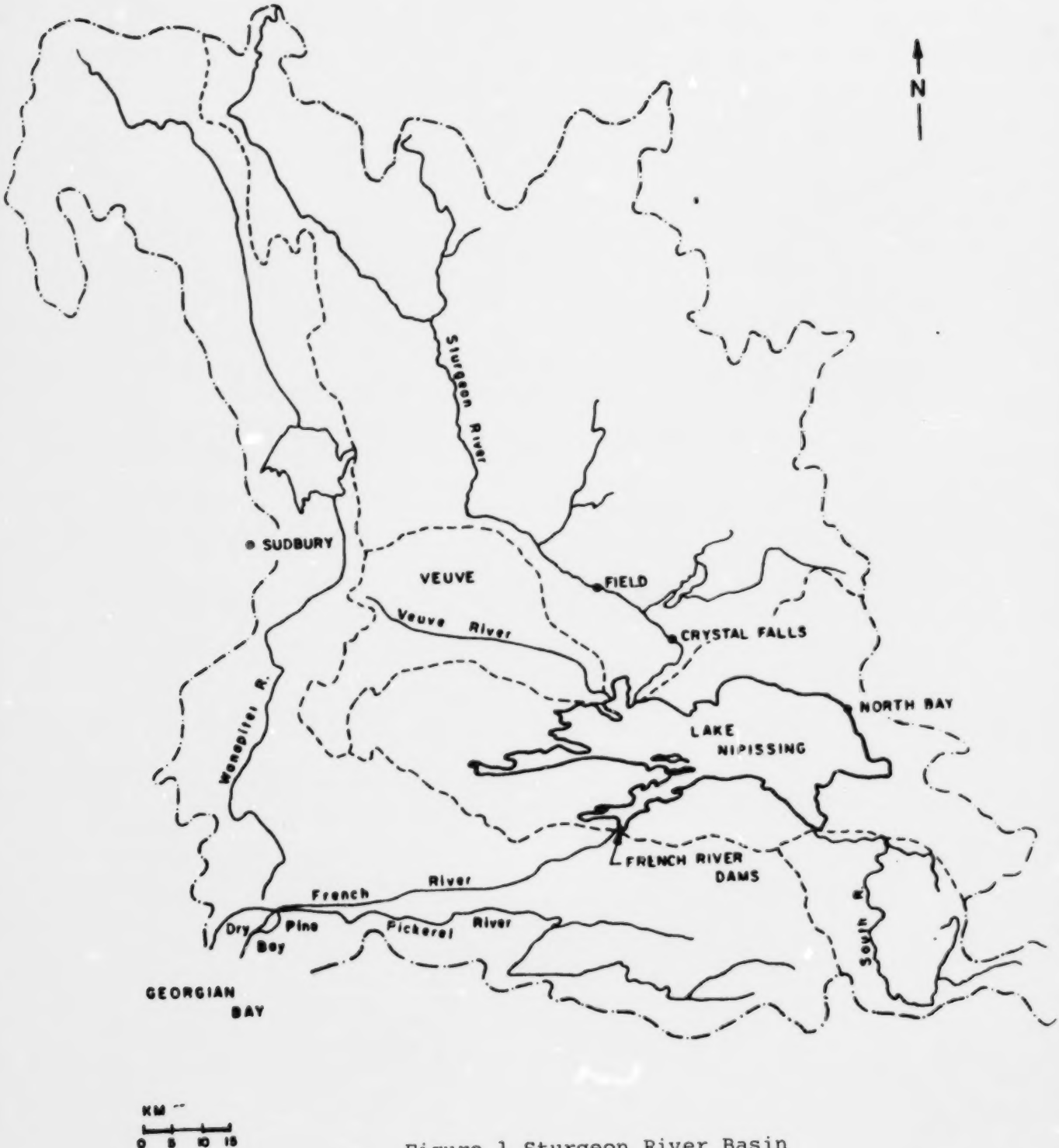

Figure 1 Sturgeon River Basin

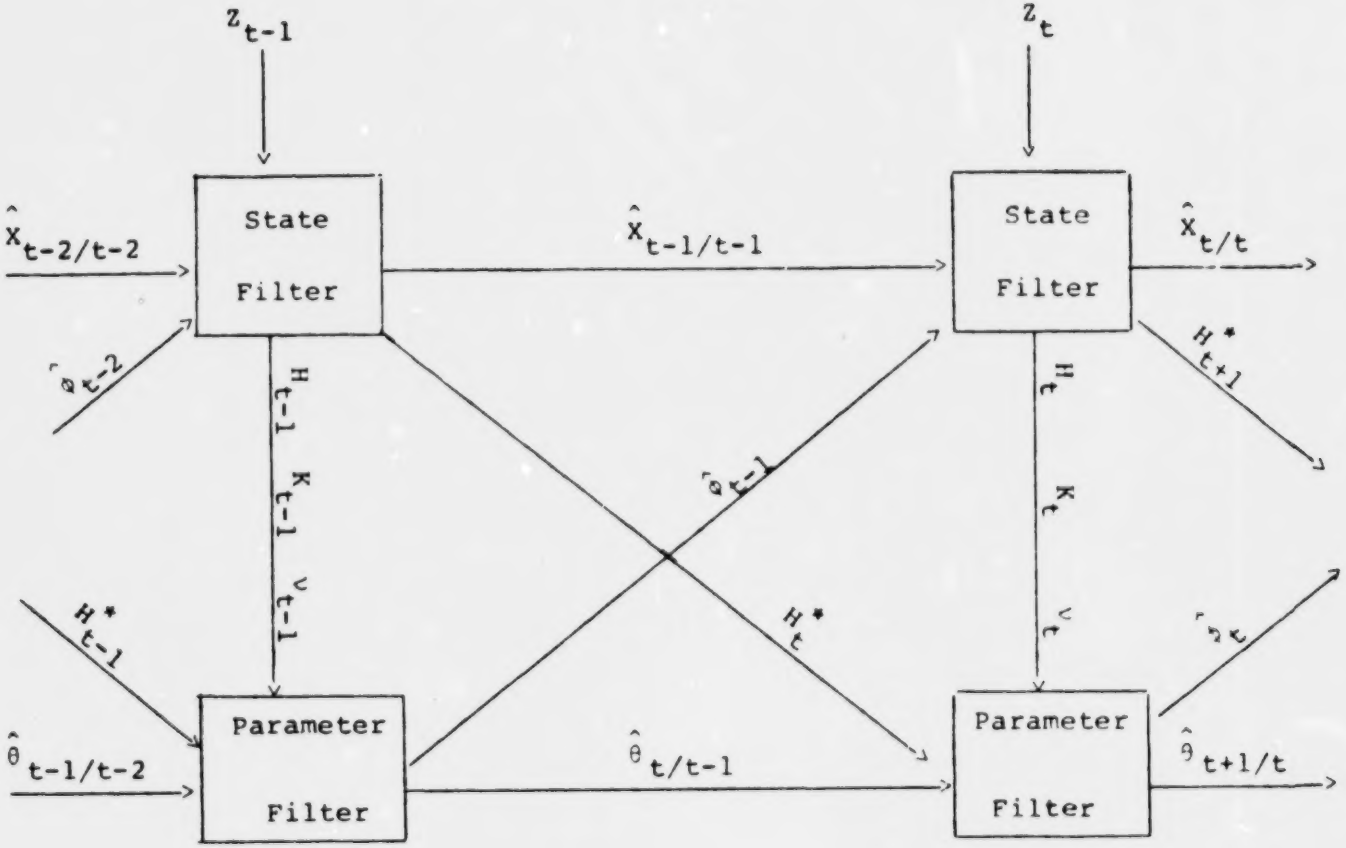

Figure 2 Transfer of Information between Filters

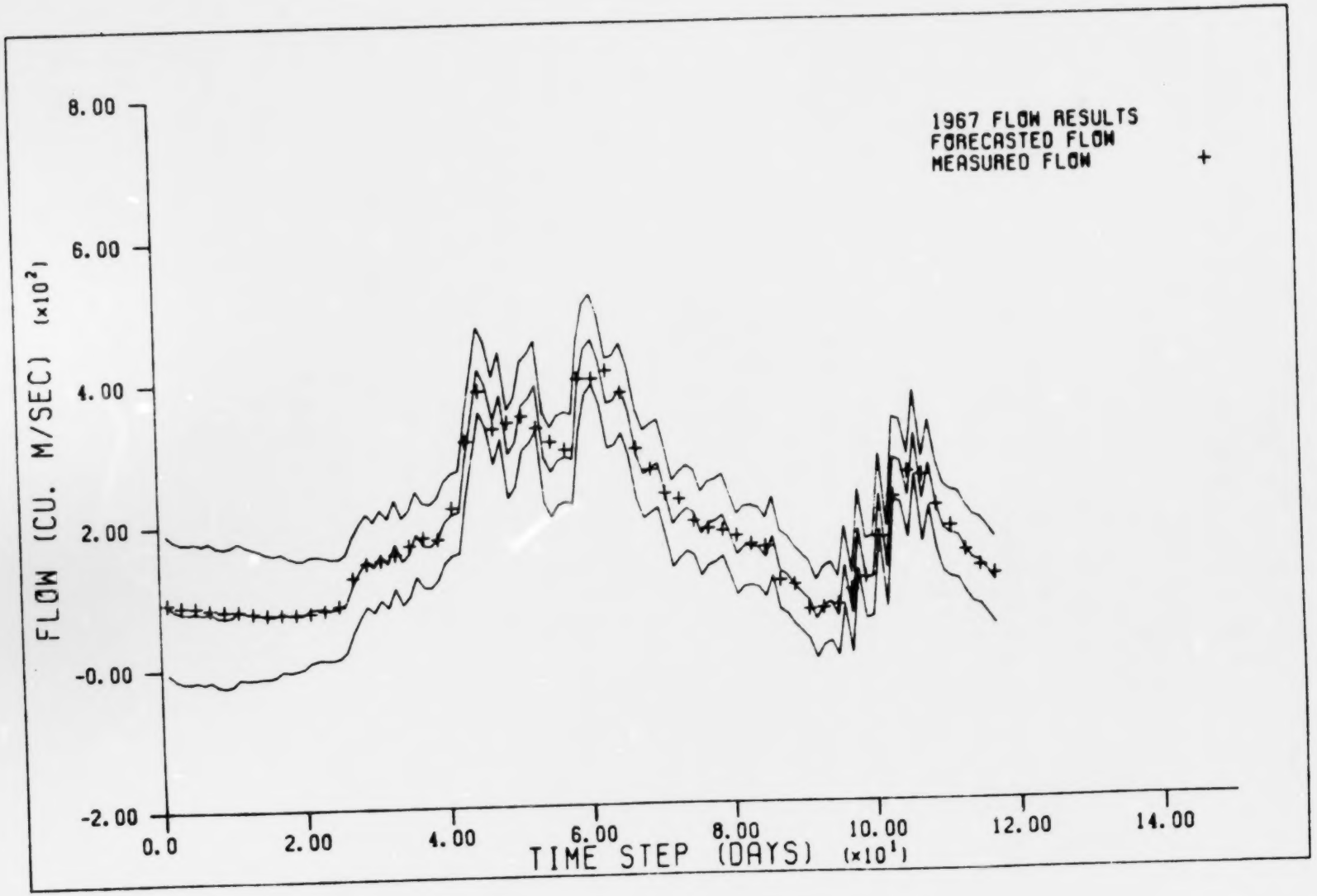

Figure 3 Results of Forecasting for 1967

A SIMPLIFIED STREAMFLOW FORECASTING MODEL FOR A SMALL WATERSHED

BY
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SENIOR HYDROLOGIST
MACLAREN PLANSEARCH INC.

ABSTRACT

Because of potential upstream flooding problems and the need to optimize power generation, a method of forecasting short-term inflows to the headpond of the Annapolis River Tidal Power pilot project was required. A lead time of between 4 and 12 hours was required to allow for drawdown of the headpond for flood storage purposes. A single flow gauge currently monitors an upstream tributary of the watershed. However, model simulations indicated that because of the character of the watershed this would be ineffective as a leading indicator of flows at the point of interest. Hence a technique based on using measured precipitation to model flows with a watershed model was developed. Real-time flow information was incorporated to update the model parameters and the estimated antecedant conditions for model forecasts.

The model, known as QFORECAST, was tested using nine years of daily data from the upstream gauge and four major flow events from the period of record on an hourly basis. Full implementation of the model awaits development of a complete real-time hydrometric data collection system and availability of on-site computer facilities.

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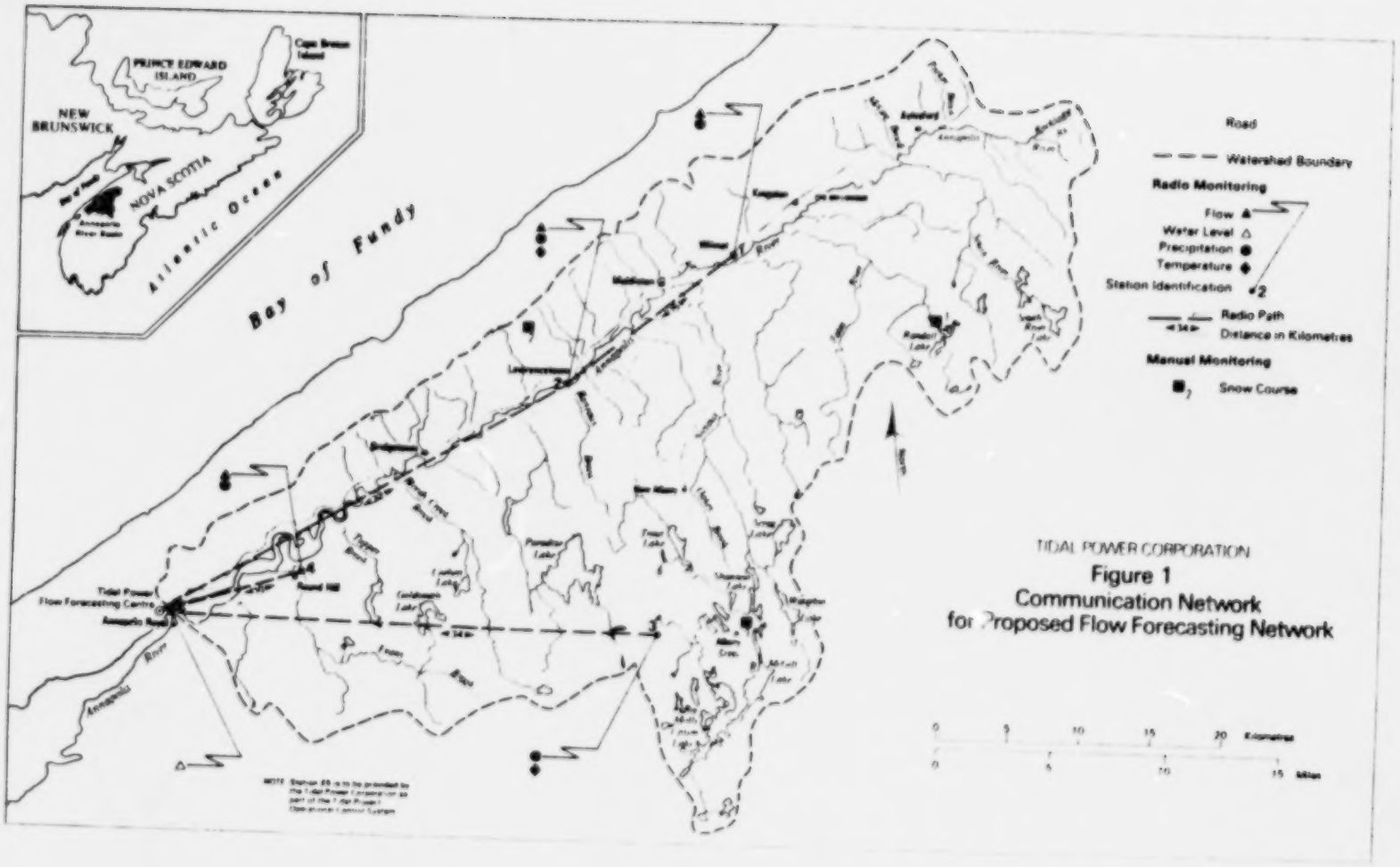
INTRODUCTION

The Annapolis River Tidal Power Project is currently being developed by the Nova Scotia Tidal Power Corporation as a demonstration of the feasibility of tidal power generation. An existing barrage at Annapolis Royal (shown on Figure 1) has been modified to incorporate a power house containing a large diameter STRAFLO turbine. This system will generate power by storing water upstream of the barrage during high tide and releasing it during low tide.

This modification of the natural flow of the river, however, increases the risk of upstream flooding during periods of high river flow. A potential method of counteracting this risk is to drawdown the elevation of the headpond prior to a period of high inflow. This clearly requires forewarning of the magnitude of future inflows. In addition, on a day-to-day basis, inflows will influence the most efficient operation of the generating system. Hence forecasting inflows to the headpond also has possible economic benefits.

In view of these incentives to the creation of an inflow forecasting system, MacLaren Plansearch Inc. was retained by the Nova Scotia Tidal Power Corporation in 1980 to develop such a system.

The initial phase of this study involved a general evaluation of the watershed characteristics and of the existing hydrometric network. It was concluded that the existing data collection network was inadequate for accurate forecasting. A system of four real-time flow and precipitation gauges was


PRINCE EDWARD ISLAND
NEW BRUNSWICK
NOVA SCOTIA
Atlantic Ocean
Bay of Fundy
Road
Watershed Boundary
Radio Monitoring
Flow
Water Level
Precipitation
Temperature
Station Identification
Radio Path
Distance in Kilometres
Manual Monitoring
Snow Course
TIDAL POWER CORPORATION
Figure 1
Communication Network
for Proposed Flow Forecasting Network

recommended as shown in Figure 1 (see Conetta and Bishop, 1982 for further details).

It was also determined from watershed model simulations that forecasting on the basis of streamflows alone would provide inadequate lead time. Hence a simple watershed model, HYMO, (Williams and Hann, 1972) was selected for use in predicting flows on the basis of measured precipitation and temperatures.

This paper describes the incorporation of the HYMO model into a real-time forecasting model, known as QFORECAST, in which measured flow data are used to update certain model parameters and the states of certain variables, e.g. soil moisture deficit. Testing of the model using data from the only currently available streamflow gauge in an upper tributary of the Annapolis River basin is described. Finally a brief discussion of ongoing development of the model is presented.

BASIS OF THE FORECASTING TECHNIQUE

Where deterministic streamflow models have been used in the past for flood forecasting in real-time, for example the National Weather Service River Forecast System model (NWSRFS), it has generally been in a manner similar to that when simulating historical streamflows. In other words, the model in question was calibrated with historical data prior to the time at which it was used, i.e. calibration was "off-line", (see for example Curtis and Smith, 1976 and Smith, 1980). When an event requiring forecasting occurred, the measured or predicted inputs to the system were used with the pre-calibrated model to prepare a forecast. As Chow et al. (1983) have

indicated this process can lead to considerable error in the forecast.

As an alternative to the use of deterministic models, various models incorporating the use of Kalman filtering techniques have recently been proposed (Mehra, 1976). These generally incorporate real-time data in a feedback mechanism to update the estimated state variables of the system and in some cases also the model "parameters" (Todini, 1978). This concept of "on-line" updating using real-time data has been recently adopted to adjust the forecast provided by the National Weather Service deterministic model (Kitanidis and Bras, 1978) using Kalman filtering.

The concept of on-line updating and/or calibration of a deterministic model was also adopted in this study. However, rather than the use of sophisticated statistical procedures such as Kalman filters, a simpler approach was utilized. The technique consisted of two parts:

i) on a daily basis a simple continuous lumped model of the watershed using a unit hydrograph, the SCS method of estimating runoff (U.S.D.A., 1974), a monthly average of daily evapotranspiration and an exponential baseflow was utilized. This was sufficiently simple that the flow on any day could be expressed directly in functional form in terms of the inputs and soil moisture states within the finite memory of the system. Hence if an observed daily flow (available at the end of each day in a real-time system) did not agree exactly with that which the model had predicted then it was possible to calculate a "correction factor" necessary to force the model to fit the

observed flow. As will be seen in a later section, this correction factor was used to modify the soil moisture state and also the "parameters" of the model in that the shape of the unit hydrograph was varied, the soil moisture percolation rate and the snowmelt coefficient was adjusted where applicable.

ii) the second part of the technique consisted of the use of the HYMO model (Williams and Hann, 1972) to estimate hourly flows within a given day. The soil moisture was set at the beginning of each day using the "updated" value from the daily model. Model parameters were fixed based on previous "off-line" calibration. A correction was applied each hour by adding or subtracting the difference between the model prediction and the observed flow in the last hour from all future forecasts. However, no other "updating" was carried out on an hourly basis.

Since the "updating" of the daily portion of this model was the most unique feature of this technique, it will be described in more detail.

DETAILED DESCRIPTION OF MODEL UPDATING

As Figure 2 indicates, the daily simulation model consists of the following components:

i) a total daily input which is the sum of observed rainfall and estimated snowmelt for mean daily temperatures greater than 0°C. A degree-day method is used to estimate melt by:

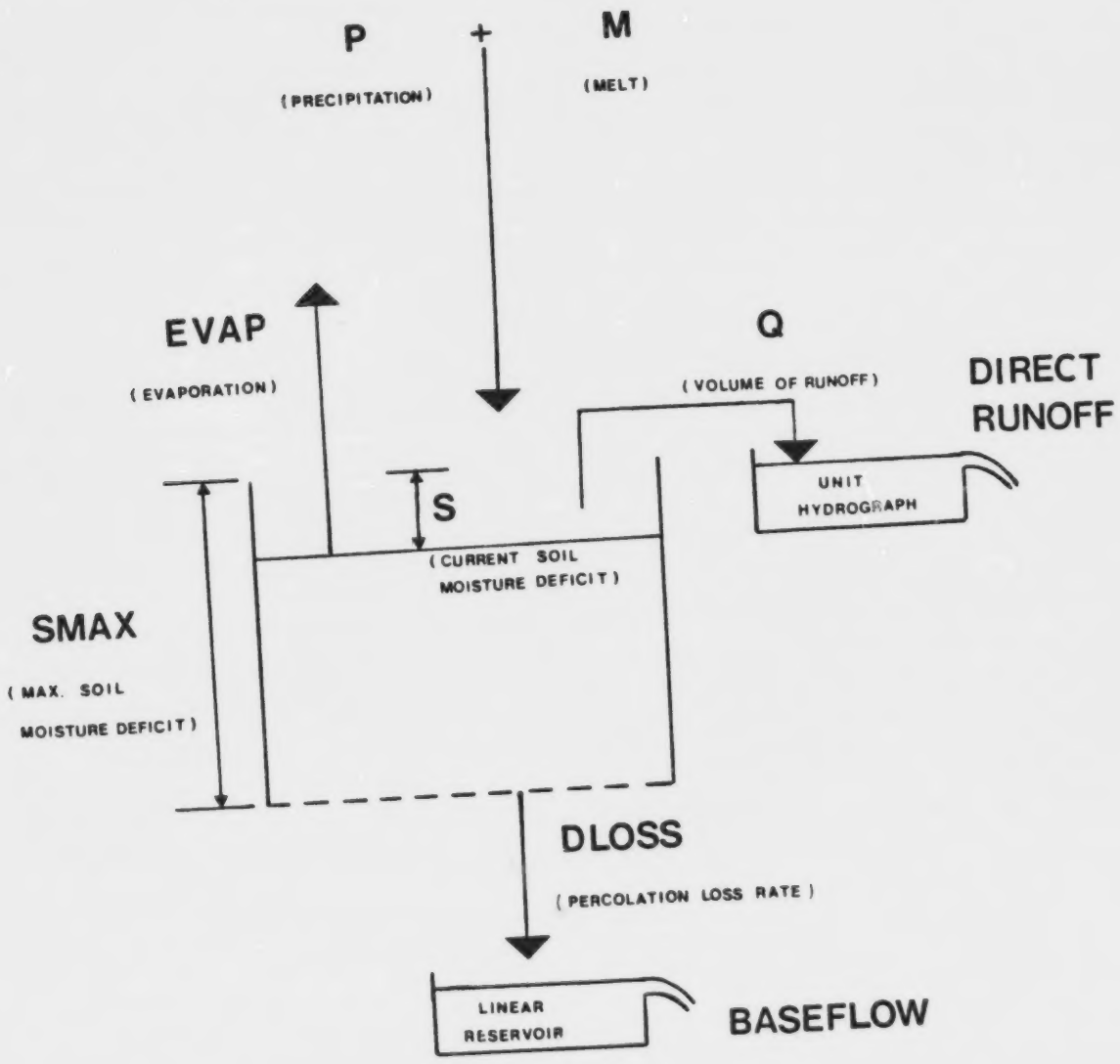


Figure 2 : Schematic of QFORECAST Model

$$M_t = CT_t$$

where: M_t is the daily melt quantity, mm
T_t is the maximum daily temperature, °C
C is the degree day coefficient.

For the case where $T_t < 0°C$ any precipitation is added to the snowpack water equivalent.

ii) a soil moisture reservoir for which a moisture budget is maintained by:

$$S_t = S_{t-1} + E_t + QD_t - (P_t + M_t) + DLOSS_t$$

where: S_t = the soil moisture deficit (with a maximum value of SMAX) at the end of the current day

S_{t-1} = the value of S for the previous day

E_t = evapotranspiration for the current day (variable by month)

$P_t + M_t$ = system input for the current day (as previously described)

$DLOSS_t$ = the loss of moisture by percolation to the groundwater system for the current day

QD_t = the direct runoff for the current day

All quantities are expressed in millimetres of moisture. Direct runoff occurs only when $P_t + M_t$ is greater than zero and is given by:

$$QD_t = \frac{[(P_t + M_t) - \alpha S_t]^2}{[(P_t + M_t) + (1 - \alpha)S_t]}$$

which is the SCS equation for runoff volume (U.S.D.A., 1972). The percolation term, $DLOSS_t$, is a function of the current moisture deficit given by:

$$DLOSS_t = DLM \left(\frac{SMAX - S_t}{SMAX}\right)^{\beta}$$

where DLM is a monthly maximum percolation rate
and β is an exponent

iii) any direct runoff is routed through the watershed using a unit hydrograph expressed in discrete form, i.e.

$$u(t) = u_o, u_1, u_2 \cdots u_j \cdots u_m$$

where u_j is the ordinate of the unit hydrograph at time t
and m is the total number of days of the direct runoff system's memory

Use is made of the convolution integral in discrete form to calculate the total direct runoff at any time.

iv) baseflow is calculated as a function of the percolation rate $DLOSS_t$ after routing through a linear reservoir with a storage coefficient, K. This can be expressed as:

$$QB_t = DLOSS_t\ (1 - e^{-1/k}) + QB_{t-1}\ e^{-1/k}$$

where QB_t and QB_{t-1} are the baseflow rates on days t and t-1.

The total flow, Q_t, on any day is obtained by summing the direct runoff and baseflow components.

With this relatively simple formulation it is possible to express the total flow on any day as:

$$Q_t = \sum_{i=o}^{m-1} \frac{[(P_{t-i} + M_{t-i}) - \alpha S_{t-i}]^2}{[(P_{t-i} + M_{t-i}) + (1 - \alpha)\ S_{t-i}]} \cdot u_{i+1}$$

$$+ \frac{C_1}{SMAX^{\beta}} \cdot \sum_{i=o}^{m} C_2^i\ DLOSS_{t-i}\ (SMAX - S_{t-i})^{\beta}$$

where $C_1 = 1 - e^{-1/k}$ and $C_2 = 1 - C_1$

Generally, of course, if this expression is used to calculate the flow on any day it will not agree with that which is reported by a real-time flow gauging station at the end of the day. However, by applying a correction factor to one or several of the terms in this equation, it is possible to adjust the calculated flow to agree with the observed flow. If the corrected terms are used in the expression to calculate the next day's flow then it would be expected that this forecast would be more accurate than without the correction.

In developing this technique the correction was initially applied to the soil moisture deficit, S. However, it was

found that distributing the correction amongst additional terms improved the model's performance. In the final version, corrections were applied to the soil moisture deficit, S, the percolation rate, DLOSS, the ordinates of the unit hydrograph, u, and the melt coefficient, C, during snowmelt periods. Calculation of the value of the correction factor, Δ, was carried out by expressing the observed flow QO_t, as:

$$QO_t = \sum_{i=o}^{m-1} \frac{\left[\left(P_{t-i} + \frac{M_{t-i}}{\Delta}\right) - \alpha \Delta S_{t-i}\right]^2}{\left[\left(P_{t-i} + \frac{M_{t-i}}{\Delta}\right) + (1 - \alpha)\, \Delta S_{t-i}\right]} \cdot \frac{u}{\Delta}_{i+1}$$

$$+ \frac{C_1}{SMAX^{\beta}} \cdot \sum_{i=o}^{m} C_2^i \frac{DLOSS}{\Delta}_{t-i} \left(SMAX - \Delta S_{t-i}\right)^{\beta}$$

and solving this equation by use of the Newton-Raphson method to find Δ. Having obtained Δ, the values of S, DLOSS, u and C were adjusted or "updated" by multiplying or dividing by Δ as appropriate. All values back to time t - m were modified but those prior to this time, i.e. beyond the "memory" of the system, can be discarded.

Since m for a small watershed may be of the order of 20 days or less, this limits the amount of data and variable storage required. In practice the values obtained for the correction factor were generally between 0.9 and 1.10 with occasionally greater variations during periods of snowmelt.

TESTING OF THE QFORECAST MODEL

The QFORECAST model was set up for the Annapolis River watershed at Wilmot (Water Survey of Canada gauge no. 01DC005) since this was the only gauge available in the study area (see Figure 1). Input data consisted of a series of precipitation and temperature records from Greenwood, located at the downstream end of the watershed for the period 1968 to 1976. Testing was carried out in two phases:

- the daily updating procedure was first tested using the entire 9 year period of data
- four events of significance were selected from the record to test the short term forecasting capabilities of the model.

a) Daily Updating Model

Initially, the model was set-up without the ability to update itself using the previous day's observed streamflow. In this form, the model is a straightforward simulation model. The model was used to simulate the period 1968 to 1976 at Wilmot. In the subsequent phase, the daily updating feature was used to resimulate the same period of flow record, 1968 to 1976. Tables 1 and 2 show the comparison of the monthly observed flows and the "observed" soil moisture deficits, respectively, with and without the daily updating feature for the period 1968 to 1970. With the updating feature, it was found that the coefficient of determination[1], R^2, for monthly flows increased from 0.79 to 0.99 and for the "observed" soil

TABLE 1

COMPARISON OF DAILY MODEL PERFORMANCE
BEFORE AND AFTER ADDITION OF UPDATING FEATURE

Year	Month	Observed Monthly Average Flow (m^3/s)	Without Updating Simulated Flow (m^3/s)	With Updating Simulated Flow (m^3/s)
1968	Jan	13.3	12.9	12.8
	Feb	8.2	11.5	8.7
	Mar	37.4	27.6	33.9
	Apr	15.8	12.8	16.2
	May	6.9	9.7	7.0
	Jun	16.2	17.2	16.3
	Jul	4.1	5.7	4.2
	Aug	2.3	2.2	2.3
	Sep	2.2	2.2	2.2
	Oct	4.5	7.8	5.2
	Nov	14.8	13.3	15.6
	Dec	26.0	25.6	24.3
1969	Jan	21.4	19.8	21.9
	Feb	19.9	14.9	19.7
	Mar	16.2	13.1	14.8
	Apr	29.7	21.9	29.8
	May	12.3	14.3	12.7
	Jun	3.9	7.1	4.1
	Jul	2.1	3.6	2.1
	Aug	2.2	2.2	2.2
	Sep	2.0	2.6	2.0
	Oct	2.0	4.6	2.0
	Nov	6.1	7.3	6.1
	Dec	20.0	13.1	18.9
1970	Jan	7.6	10.7	7.9
	Feb	19.0	13.8	19.1
	Mar	9.0	9.7	8.6
	Apr	17.8	13.6	17.4
	May	10.9	11.0	11.0
	Jun	5.2	5.4	5.2
	Jul	2.9	3.8	2.9
	Aug	2.7	3.5	2.8
	Sep	2.2	3.9	2.2
	Oct	11.1	12.9	11.3
	Nov	18.0	17.4	18.1
	Dec	12.6	13.8	12.9

TABLE 2

COMPARISON OF SIMULATED AND "OBSERVED" SOIL MOISTURE DEFICITS BEFORE SELECTED EVENTS, 1968-1970

Date	Observed[1] Moisture Deficit	Without Updating Simulated Deficit	With Updating Simulated Deficit
18 May 1968	3.63	2.74	4.09
12 Jun 1968	6.47	3.32	3.98
19 Oct 1968	9.49	4.09	5.08
17 Nov 1968	1.35	0.82	0.72
18 Apr 1969	1.73	0.88	0.75
19 May 1969	2.85	1.65	1.99
03 Aug 1969	3.39	4.24	4.32
19 Oct 1969	4.10	3.31	6.05
21 Dec 1969	0.47	0.77	0.61
11 May 1970	3.00	2.62	2.51
03 Jul 1970	3.46	3.05	2.95
10 Aug 1970	7.20	3.87	5.07
03 Oct 1970	4.30	2.37	4.13
02 Nov 1970	2.14	1.20	1.37

1) This value was calculated from the observed precipitation and runoff volume for the event by using the SCS equation in reverse.

coefficient of determination[1], R^2, for monthly flows increased from 0.79 to 0.99 and for the "observed" soil moisture deficit increased from 0.24 to 0.84. This indicates considerable improvement in the estimation of S_t, the moisture deficit, through the incorporation of the real-time updating. This provides a high degree of confidence that the daily model will provide accurate seasonally varying starting conditions for the short term forecast.

b) Short Time Step Forecast Model

Testing of the short time step forecasting part of the model was also carried out on the basis of observed flows at the Wilmot streamflow gauge. Four events were selected from the period 1968 to 1977 for which significant peak flows were experienced at Wilmot. These are known to have caused high water levels in the headpond at Annapolis Royal.

The results of the testing of the forecast performance of the model for two of the selected events are indicated by Figures 3 and 4. The first of these events occurring in July 1976 was caused by a rainfall of 107 mm on 12 July 1976. The second event in March 1972 was caused by melting snow with little or no rainfall occurring. Figures 3 and 4 indicate the model forecasts for a 24-hour period as prepared 24, 12 and 6 hours before the observed peak occurred. As expected, the accuracy of the forecast improves considerably as the lead time reduces. In both

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1) R^2 is defined as $(F_o^2 - F_1^2)/F_1^2$ where $F_o^2 = \Sigma(Q_f - Q)^2$ and $F_1^2 = \Sigma(Q - \bar{Q})^2$ where Q is the observed flow, Q_f is the forecast flow and $\bar{Q}$ is the mean flow.

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Figure 3

Comparison of Forecast and Observed Flows for Major Rainfall Generated Event at Wilmot Gauge, Annapolis River

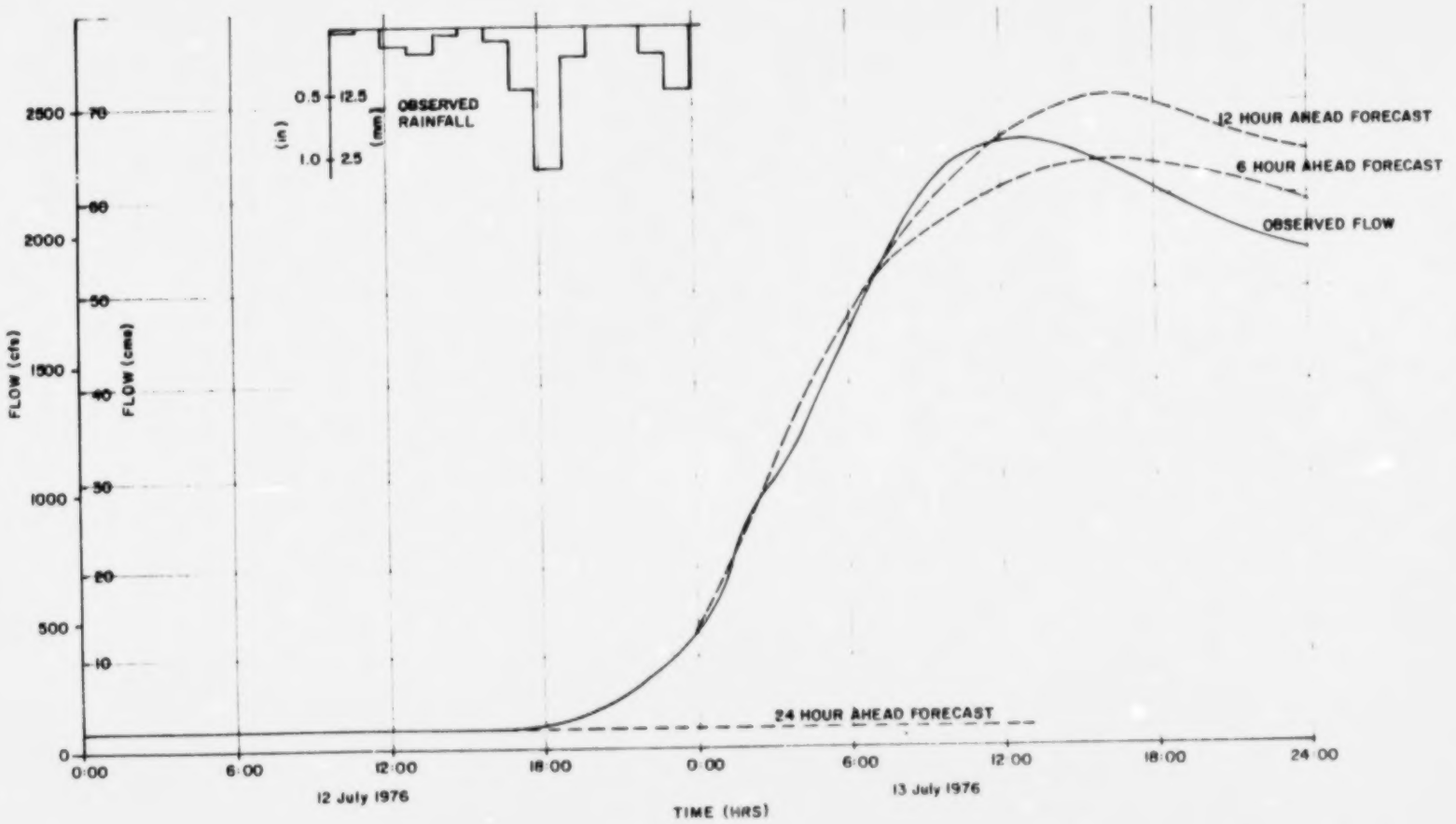

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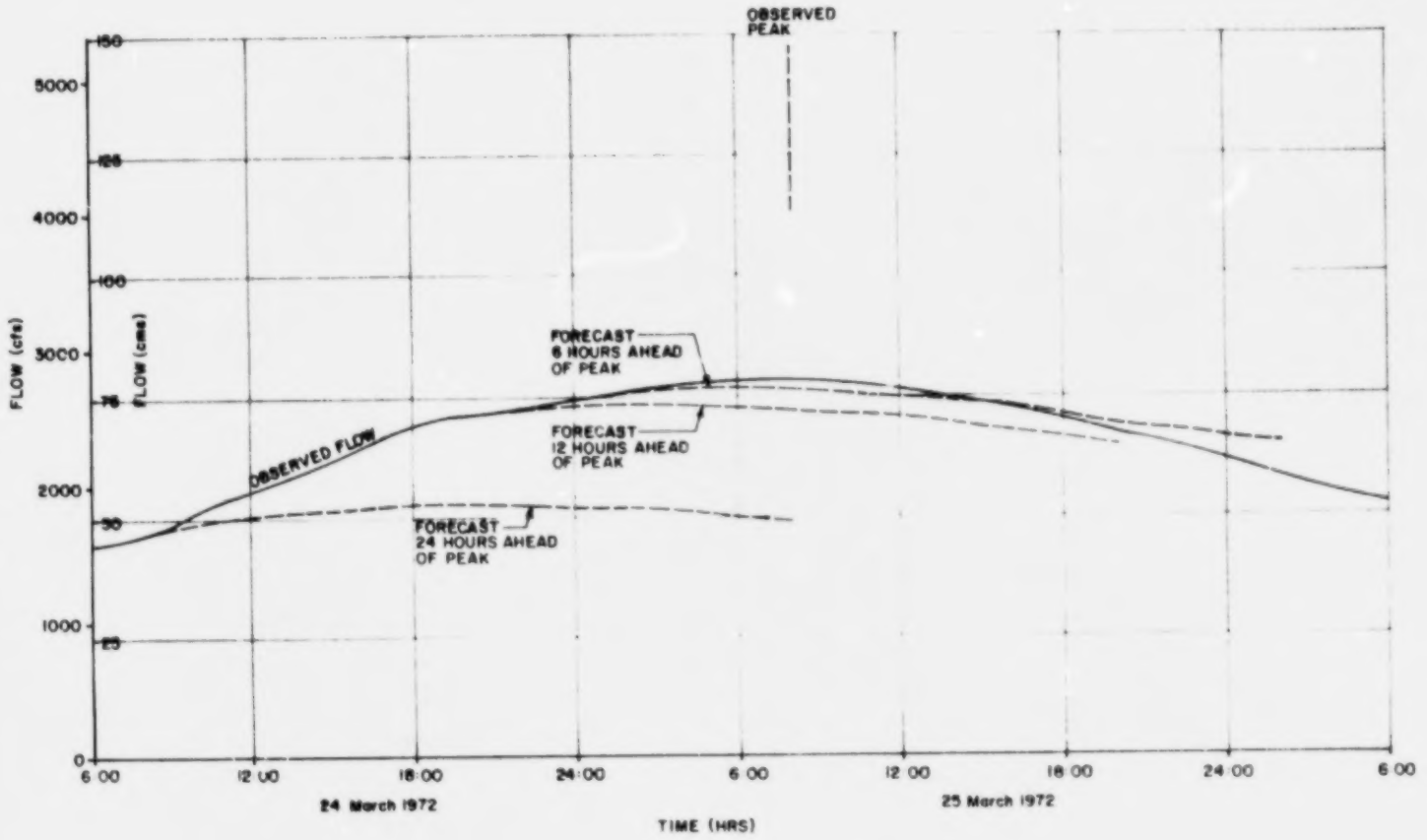
Figure 4

Comparison of Forecast and Observed Flows for Typical Snowmelt Generated Event at Wilmot Gauge, Annapolis River



cases, the 12 hour ahead forecast is within 15 percent of the observed peak while the 6 hour ahead value is within 10 percent. The 24 hour ahead forecast in both cases is relatively poor. This is because the inputs to the system, i.e. precipitation and snowmelt, have not as yet occurred and, therefore, have not been reported by the data collection network. The forecast performance improves dramatically once the input has occurred. This is clearly illustrated by the July 1976 event. As indicated in Figure 3 the forecast 24 hours ahead of the observed peak shows the flow in the river continuing to slowly recede. Once the input has occurred, i.e. about 12 to 17 hours ahead of the peak, the model predicts the observed flow within 5 percent.

Further measures of the accuracy of the short time step forecast model are shown on Figure 5. These are:

i) the coefficient of determination, R^2, of the agreement between the observed and forecast hourly flows for different forecast lead times. This value indicates the degree to which the model is better than using the latest recorded flows as a forecast of the future flows. It is a fairly rigorous test of the model suggested by Watt and Nozdryn-Plotnicki (1979) and values of 0.5 or greater indicate excellent agreement between the forecast and observed values. Table 3 indicates the coefficient of determination for the hourly forecast model for various lead times. As can be seen the values averaged over the four test events are 0.48 and 0.51 for the 6 and 12 hour lead times, i.e. the range of lead times of

TABLE 3

COEFFICIENTS OF DETERMINATION FOR HOURLY FORECAST MODEL FOR VARIOUS LEAD TIMES

Event No.	Date	Forecast Time Lead (Hr) 1	6	12	24
1	Mar 1972	0.37	0.49	0.42	0.12
2	May 1972	0.36	0.32	0.17	0.05
3	May 1976	0.13	0.33	0.45	0.35
4	Jul 1976	0.45	0.79	0.69	0.28
Average		0.33	0.48	0.51	0.20

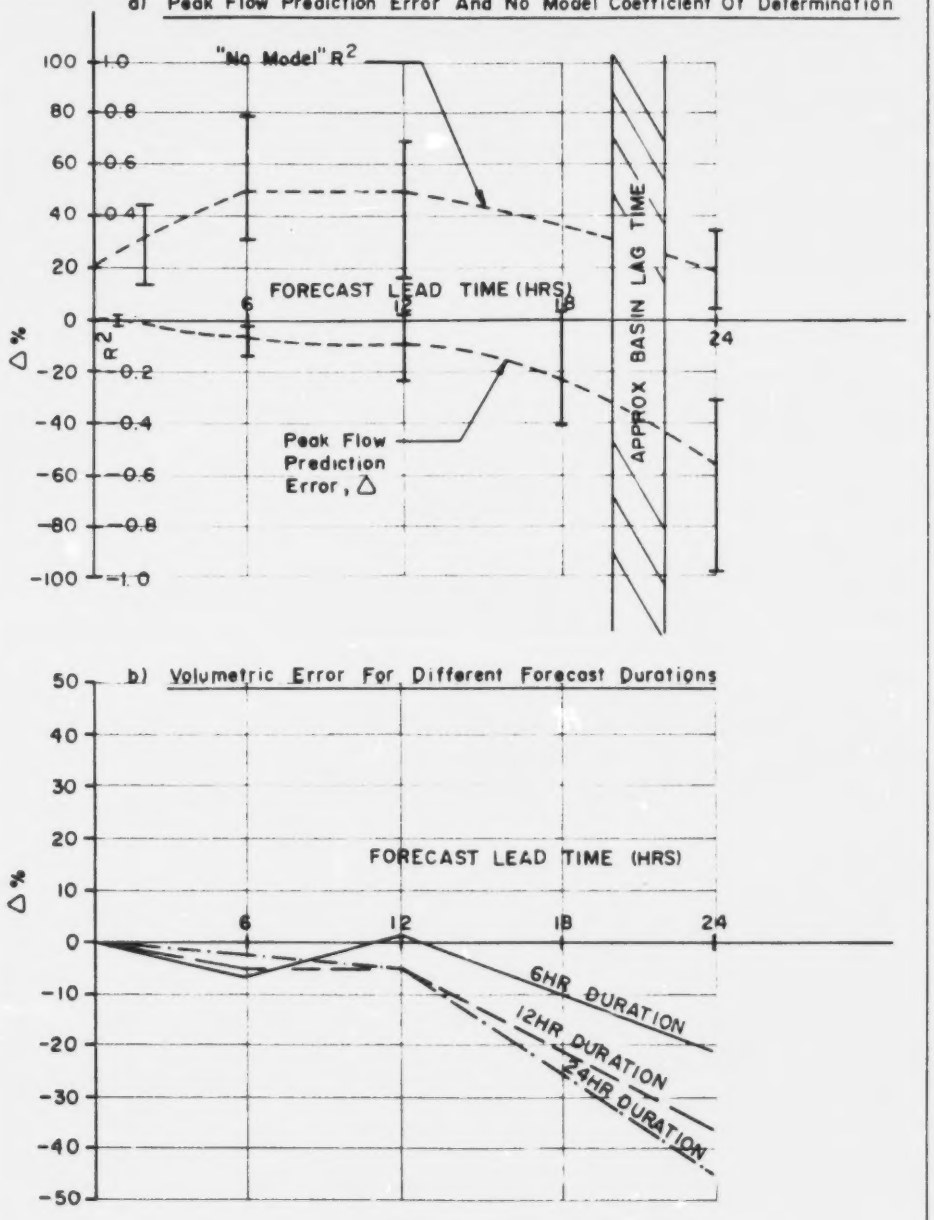


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Figure 5

Accuracy of Short Time Step (1Hr) Forecast Model

interest. As expected the accuracy drops considerably for lead times of 24 hours.

ii) the average accuracy of the peak flow prediction for different lead times for the four tested events is shown on Figure 5a. The agreement is better than 10 percent for lead times of 12 hours or less, gradually improving as the lead time shortens. Beyond the basin lag time the accuracy falls considerably to about 50 percent.

iii) the difference between observed and forecast volumes of runoff for different durations for different lead times. For example, the model's performance in predicting the total runoff volume over the next 6 hours at times 6, 12 and 24 hours before the observed peak flow is shown in the upper curve of Figure 5b). Again, the accuracy is good, i.e. within about 5 percent up to 12 hour lead times for all durations shown. As expected major differences occur for the 24 hour lead time. The only manner in which forecasts at this lead time could be improved would be through the incorporation of accurate precipitation and temperature forecasts for the area.

DISCUSSION

i) Testing of the model indicated that its performance in the real-time forecast mode is quite acceptable. In this mode, the model always provides a significant improvement over the use of the latest flow recorded by a real-time data network as a forecast (as indicated by R^2).

ii) There are clearly several areas in which the model could be improved, namely:

- in its current form the updating technique assumes that all the 'error' in estimating the flow on a given day is caused by errors in either the parameters of the model or the modelled variables such as soil moisture deficit. Clearly there are inaccuracies in the input information, particularly precipitation data. A method of detecting such errors would help prevent the updating technique from "over correcting" on occasions when the input data is significantly in error.

- in its current form the updating technique distributes the "correction factor", Δ, evenly throughout the components to which it is applied. Further investigation may reveal that more weight should be given to certain components rather than others.

- the short term forecast based upon the HYMO model is not directly updated during a particular day. The only correction applied is to adjust forecasted flows to account for the difference between the observed flow in the past hour and that predicted by the model. There is a tendency for the forecasts to become less accurate as a day progresses. In addition, since the HYMO model parameters, particularly the unit hydrograph timing parameters, are fixed from earlier off-line calibration, the timing of the forecast peak remains fixed once the input to the watershed has ended. An hour-by-hour 'updating' of

the hourly model would improve the short term forecast performance but would increase the computation expense considerably.

iii) Since the technique is relatively simple and requires storage of only a limited amount of data it should be feasible to implement it on a microcomputer. Given the plummetting cost of these devices it would then be possible to implement such a system on a small watershed for which the resources necessary to use a complex conceptual type of simulation model would not be available. Implementation on a commonly available personal computer is currently under investigation.

iv) The basis for this forecasting technique is the widely used HYMO model and the SCS method of runoff volume computation. These have been widely used in watershed planning studies throughout Canada. The QFORECAST model could therefore be relatively easily implemented in these situations since much of the background data collection and model calibration required would already have been completed.

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Meteorological Inputs to Streamflow Forecasting

by

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ABSTRACT

Streamflow forecasting in Canada demands meteorological information for a variety of purposes and applications. This paper describes how meteorological data are processed and applied to operational hydrology. The results of recent forecast verification studies are presented, along with an indication of the plans for better forecasts and alternative observational sources up to 1990.

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1. Introduction

Atmospheric processes are an integral and determining part of the hydrological cycle and the link between weather and streamflow is both obvious and strong. The link between weather and water agencies in Canada is not nearly so clear.

Under Canada's federal system, water within provincial boundaries is considered a provincial resource while weather is generally accepted as a federal responsibility. In addition, a federal agency is responsible for maintaining a national inventory of water resources and for coordinating projects and programs involving water crossing provincial and international boundaries. Some provincial governments have developed their own expertise to support meteorologically sensitive provincial programs and to investigate micro- and macro-scale climate variability. In most regions of the country then, a provincial agency is responsible for flood forecasting, water level management and structural design criterion; a federal agency (Inland Waters Directorate) responsible for measuring flows and water levels and coordinating boundary water projects and a second federal agency (Atmospheric Environment Service) responsible for weather forecasting, precipitation measurement etc. Both federal agencies are part of Environment Canada.

Regardless of the mandates involved, streamflow forecasters require meteorological information. For small urban basins, measurements and forecasts of events as small as individual thunderstorms with time scales from minutes to six hours are critical. Basins of a few thousand square kilometers are sensitive to meteorological phenomena which display a larger scale structure and organization. Areal distribution of meteorological parameters on a time scale of a few hours is relevant for these basins. For Canada's larger rivers, snowmelt and motions of synoptic scale storms are important for flow forecasting. Regardless of basin size, meteorological observations, interpolations and forecasts are needed but specific products vary markedly in both form and timing, dependent upon application.

2. Defining the Streamflow Forecast Problem

In the design of a streamflow forecast operation, the first question the hydrologist should ask himself is: what is the main purpose or use of the streamflow forecast? This could be the issuance of flood warnings throughout the year (or part of the year) for one populated area (or many) which is threatened by floods from a large (or small) river. On the other hand, the objective could be multi-purpose, such as maximizing the storage of water in a reservoir while minimizing downstream flooding. In any case, the precise and early definition of the main hydrological problem and the linking of this problem (or problems) to the meteorological information available will produce a much more effective streamflow forecast.

As will be discussed in more detail below, the main emphasis of the meteorological forecast system, is prediction of synoptic scale weather pressure systems over typical lifetimes of one to three days in advance. The system is based on a synoptic observational network made up of stations 100 to 150 km apart, reporting every six hours and a numerical prediction model with roughly the same resolution in time and space. Short term weather warnings are a refinement of the synoptic observations and model output, combined with other information, such as radar and satellite data and hourly aviation weather reports, which is useful for identifying the cause of the warning and for extrapolating it into the near future.

The streamflow forecaster may want to produce forecasts for a variety of uses, ranging from extremely local flash flood warnings to the regulation of monthly flows on the Great Lakes, for example. As shown in Table 1, the meteorological "trigger" for hydrological events varies in size, lifetime and predictability. A severe thunderstorm may cause heavy local flooding in one part of a town but not be predictable, in quantitative terms, for more than an hour or two - or even observed and identified from a synoptic network. On the other extreme, the forecast of critically low flows on a major river is often the result of a prolonged drought where the significant meteorological trigger is the net effect of very warm temperature and dry days, accumulated over several weeks or months. Neither of these hydrological events are easily deduced from a synoptic scale forecast without a much finer network of observations or a seasonal monitoring and predictive capability. Fortunately, the typical spring flood on large rivers in Canada is the result of heavy snowmelt and rainfall over several days which usually match the scale of the meteorological forecasts.

Another significant point to note from Table 1 is the relative importance of various meteorological parameters relative to the hydrological problem. On the short time scale, rainfall may be the only important parameter and such factors as temperature, humidity, wind, evaporation and radiation are secondary or negligible in producing an accurate streamflow forecast. For the timing of the maximum monthly flow in major Prairie's streams, the most important parameter is the condition of the winter snow pack in the mountains. Similarly in large scale droughts, the low flow is a function of dry soil, high evaporation and lack of precipitation which in turn is strongly influenced by wind speed and solar radiation. The difficulty in forecasting various meteorological parameters can be appreciated by comparing the maximum lead times associated with each hydrological event, ranging from under two hours for quantitative forecasts of heavy rainfall to two or three months qualitative indications of large scale droughts.

The importance of rationalizing the needs of the flow forecast centre to the strengths of the meteorological inputs is clear. What is often overlooked is the identification of gaps in the meteorological network, an appreciation of the difference in scales between hydrology and meteorology and the extent to which meteorological forecasts can be usefully applied. For further reading on the linking of hydrological requirements and meteorological capabilities, WMO (1980) contains the results of a three year pilot project on the Saint John River Basin, involving sixteen U.S. and Canadian agencies.

Table 1

Streamflow Problems and Meteorological Triggers

Hydrological Problem	Meteorological Trigger	Size of Trigger km^2	Maximum Forecast Lead Time	
			Quant.	Qual.
1. Flash Floods				
a) heavy rain on saturated soil	thunderstorm	10	2 hr	12 hr
b) moderate rain on frozen ground	synoptic or meso-scale rain storm	100-1000	24 hr	48 hr
c) ice jam	sudden thaw and light to moderate rain	10,000	3 days	5 days
2. "Hybrid" Floods	moderate to high snowmelt and rainfall over 1-2 days	10,000	24 hr	2 days
3. Annual Maximum Discharge for Water Supply Regulation	heavy winter snowfall and onset of spring thaw	continental	2 weeks	1 month
4. Annual Minimum Discharge for Water Supply Regulation	drought (prolonged heat and dryness)	continental	1 month	2-3months

3. The Meteorological Observing Network in Canada

The Atmospheric Environment Service (AES) perceives the hydrological community as an outside user with a possible requirement for any or all of the data collected by the Service. Its data collection networks are generally not specifically designed for hydrological purposes. The national meteorological observing network consists of 2600 climatological stations taking measurements daily out of which 330 "synoptic" observations are taken and transmitted at least every six hours. The growth of the conventional climatological observation network has reached a definite plateau in number of stations. In addition to these manual observations, AES has 50 automatic stations and 128 long duration recording precipitation gauges located in remote regions which are important for calibration of the hydrological models.

Climatological data are accessible to all, including hydrologists. In fact, specialized hydrometeorological analyses of the archived data are regularly performed and distributed (Hogg, 1980). Included in these special analyses, objective network planning techniques have been applied to precipitation gauge data in several parts of the country to assess network gaps and gauge density requirements (e.g. Mapanao and Pugsley, 1977; Johnstone, 1983; Saulesleja and Louie, 1983). As part of the monitoring role of the Canadian Climate Centre of AES, near real-time water budgets for Canadian and northern U.S. stations are being processed. Derived components from the model include estimates of evaporation, soil moisture, snow pack water equivalent and snowmelt. Weekly accumulation and averages of these components are mapped and distributed about two days after the end of the week.

The provision of meteorological data and services to the hydrological community within minutes or hours of the time of observation is a more difficult problem which in the past has been solved in a variety of ways. Due to the split jurisdiction at the weather/water interface, considerable diversity exists across the country in the forecast programs which have been set up. This diversity exists both with respect to streamflow forecasting itself and also with respect to the tailoring of meteorological inputs by either the AES or the provincial/private entities involved.

The most basic level of service provided is the timely transfer of data on meteorological events which have already taken place or are taking place at the time. Such transfers span a wide range of data types and communications technologies. The simplest, which takes place in most Regions, is a transfer of daily maximum and minimum temperatures and 24-hour precipitation values by telephone or telex (often computer-to-computer). Volunteer climate observers may be contacted directly by water management agencies or special bulletins may be formatted and sent by computers at AES Weather Centres. On a more sophisticated level, river forecast centres often receive hourly data plus the entire gamut of AES's routine forecasts and bulletins on dedicated user circuits (through CN/CP teletype). DCP data may be programmed to be received by the same method. Major river forecast centres also utilize the output of radar and satellite sensors via drops on paper or photo facsimile distribution circuits.

Technological advances in the data collection field have provided both the opportunity to respond to additional requirements plus demands for a system to distribute the new forms of information. Digital satellite and

radar data are now more accessible. Growth of available computing power has enabled these high volume data bases to be readily processed to estimate such fields as precipitation, surface water temperature and snow cover. The capabilities of the national weather radar network (Figure 1) continue to expand significantly. Maps from all of the network radars can be accessed through dial-up facilities. Digital data are available from two sites in real time and five sites climatologically. Both capabilities will be expanded to the entire network over the next few years. AES operates four weather satellite readout stations to obtain data from both the polar orbiting NOAA series and the GOES-VISSR satellites. The main product continues to be images for use in weather offices but several techniques for analysis of digital data have been developed. AES airborne radiometer surveys of the Great Lakes have produced reliable and timely lake surface temperatures since 1966. The aircraft surveys have been very successfully replaced by analyses based on digital infrared data from NOAA satellites. Comparison with conventional surface measurements shows a standard error of only 0.6°C for the corrected satellite data. The resultant water surface temperature maps are used to estimate evaporation rates for flow forecasting and regulation of the Great Lakes water levels. Two techniques to determine the areal extent of snow cover from satellite data are also in use. A supervised classification technique has been implemented to fully utilize the multispectral digital data from NOAA satellites (see Waterman et al 1980). Map registration of the satellite data permits automated snow cover assessment sub-basin by sub-basin. A density slicing technique uses images and much less expensive equipment to independently estimate snow cover areal extent. Both techniques are used during snowmelt seasons to assess snow cover in the Saint John River Basin as part of a Federal/Provincial agreement on flood forecasting.

Canada's vast territories with low population densities make auto-stations and satellite data collection platforms (DCP's) very appealing to a wide variety of users. AES currently operates 71 auto-stations and DCP's, communicating via either land line or satellite. ECS has approval to install 350 hydrological DCP's over the next five years. Many of the sites are desirable meteorologically and AES is seeking funding to put meteorological sensors at a portion of the sites. In anticipation of continued rapid proliferation of DCP's in Canada and to ensure coordination and standards for the acquisition, communication and archiving of DCP data, an Environment Canada policy (Environment Canada, 1983) has been published. This should serve as useful guidance for both government and private sector operators of platforms. For streamflow forecasting, timely access to data remains the major concern and communication links the most serious problem. Data are distributed through dial-up links in Suitland, Maryland (NESS) or Prince Albert (IWD) or from AES communication lines. A large percentage of data seem to be lost or delayed in the links between the satellite and the user.

4. Forecast Products

In order to deal with the fast response of small watersheds and to lengthen warning times in larger watersheds with a slower response dominated by snowmelt, recourse must be made to meteorological forecasts. In certain cases, tailored special forecasts and bulletins are prepared in AES Weather Centres. These often involve the extraction and compilation of relevant observations from the data base and the extraction and adaptation of forecast values from a variety of numerical weather prediction products available from

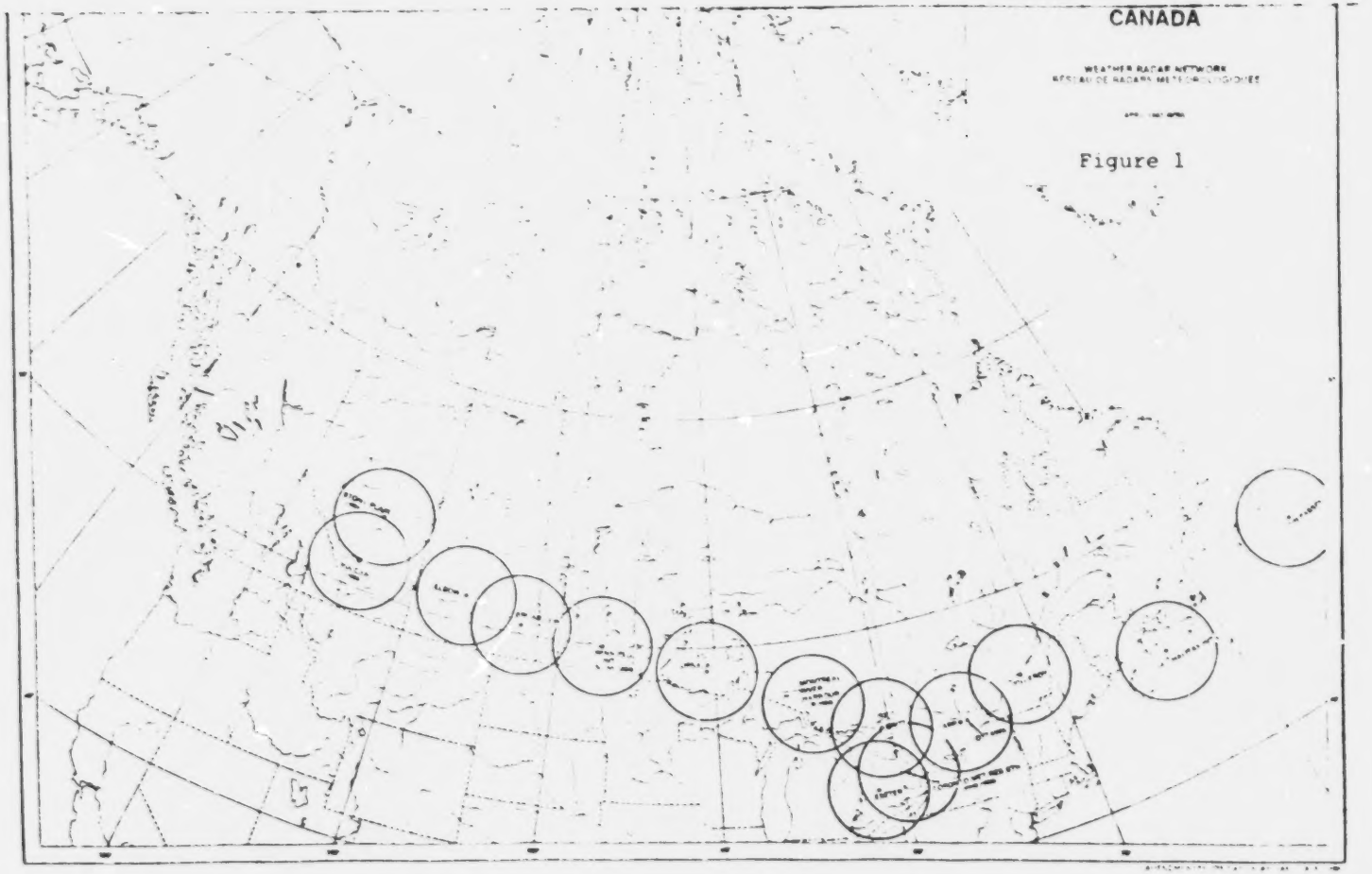


Figure 1

the Canadian Meteorological Centre or from U.S. sources. In such cases use is also made of locally produced forecasts and warnings as part of a consistent daily output package prepared by the Weather Centres. In other cases no special forecasts are prepared but Weather Centres either initiate consultations or are available for such exchanges as situations warrant. In at least one case (the Saint John River Basin), numerical weather prediction products go directly to a flow forecast centre for further machine processing and input to a hydrological model, with, during the freshet, manual modification at the Weather Centre level.

Forecast products can be grouped into three categories based upon the length of the forecast period:

i	0-6 hours
ii	6-24 hours
iii	beyond day one

Each category involves different scales of systems and requires different forecast techniques. The 0-6 hour forecast usually involves detailed observation of existing phenomena and extrapolation of them, unmodified. Spatial and temporal scales of the forecast must be fine and distribution prompt in order for the product to be useful. Radar and satellite mapping of thunderstorms, extrapolation of their motion and projection of rainfall accumulation along the path is a typical example of the 0-6 hour forecast. In fact, exactly this procedure has been automated using radar data (Bellon and Austin, 1978) and implemented in one AES Weather Centre (Quebec). Implementation of similar capabilities in the remaining Weather Centres is scheduled to be completed by 1987. A similar system using satellite and radar data and referred to as RAINSAT (Bellon et al 1980) is being evaluated as a source of forecasts in areas without radar coverage but field implementation is several years off.

Several meteorological scales are important to forecasts for 6-24 hours. The lead time is short enough that fine scale information is required by the user but too long for simple extrapolation of existing features. Control of the development and motion of individual storm cells by the larger synoptic scale systems and energy transfer between the scales must be considered within the complex numerical weather prediction models. But observational input to forecast models and the output of the models themselves are still very much only for the synoptic scale. The result is that forecasts are necessarily less specific than users want, especially for parameters like precipitation when convection (i.e. thunderstorms) is involved. Thus, instead of forecasts of specific amounts for points or basins, predictions often must be couched in terms of identifying areas within which heavy rain may develop. Quantitative precipitation forecast (QPF) products are produced by the various models of the atmosphere run by Canadian and American numerical weather prediction centres but, even in the absence of convection, there are many fine scale processes in action contributing to local extremes which not even the most accurate QPF product could hope to predict. Probability of precipitation amount (POPA) forecasts are also available for this time segment for 72 stations across the country but the same constraints due to scale apply equally to POPA since both the derived statistical relationships and the predictors are based only on the synoptic scale. Precipitation forecast products will be discussed more fully in Section 4.2. Prediction of finer

scale detail in the 6-24 hour period is dependent upon meteorologists in regional weather centres refining the synoptic scale guidance material using their knowledge of local topography and meteorological phenomena.

Beyond day one the user is more able to accept general or regional type forecasts as obtainable from synoptic scale numerical guidance. Of course, imperfect parameterization of the numerical weather prediction models and the influence of phenomena smaller than the resolution of the synoptic observation network, combine to increase the likelihood that the predicted state of the atmosphere will deviate significantly from the actual as forecast time increases. In other words, the further into the future the forecast is, the less skill it usually has.

In any event, no matter what time period or spatial scale is being considered, the forecast is strongly influenced by the synoptic scale numerical guidance available in the regional weather centre. Some of these products will be discussed further to provide some insight into the degree of uncertainty in the weather forecasts coming to the flow forecaster.

4.1 Numerical Forecast Products

4.1.1 Temperature

The Canadian Meteorological Centre forecasts of maximum and minimum temperatures are made for a set of 160 stations out to day 5. Forecasts out to day 3 are transmitted twice daily, the longer range forecasts for days 4 and 5 are transmitted once. Skill is shown in the forecasts out to the minimum temperature on day 5 with negative skill for the maximum temperature for the fifth day. The skill varies seasonally and geographically, and is generally higher in Eastern Canada than in the west and the Arctic. The verification score used is the percent improvement over climatology (percent of variance explained) on a national basis. Scores for the new model are available since November, 1982 and are shown in Table 2.

TABLE 2

Verification of Minimum and Maximum Temperature Forecasts
for 160 stations in Canada
(Percent improvement over climatology)

DAY 1		DAY 2		DAY 3		DAY 4		DAY 5	
min	max	min	max	min	max	min	max	min	max
65	69	55	52	39	33	25	10	13	-12

Fifteen day forecasts of temperature anomalies are prepared daily for each of 70 Canadian stations using analog techniques. The product is prepared by searching historical weather maps to find cases similar to the present one. The present situation is defined by the sequence of charts for two weeks leading up to today's chart plus the 500 mb 48 hour prognostic chart. After the five best sets are selected, the surface temperature anomalies are calculated for the fifteen following days. The results of the five separate forecasts are averaged to provide a concensus forecast. Forecasts are given

in five ranges much above, above normal, below and much below normal. Verifications of these forecasts show marginal skill over climatology and persistence and are more reliable when the extreme ranges are forecast.

4.1.2 Precipitation

Numerical weather prediction guidance in several forms is available from both the U.S. and Canadian Meteorological Centres. The U.S. National Weather Service runs what is referred to as the Limited Fine Mesh Model (LFM) while the Canadian Meteorological Centre (CMC) runs the Spectral model. Both models use the physics of the atmosphere to describe its present and future states but the CMC Spectral model uses a spherical harmonic series expansion of up to 29 waves to extrapolate to a future time step. A detailed comparison of the models is available in AES (1982).

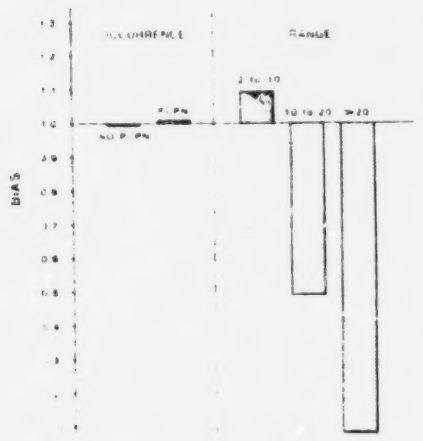
As might be expected, the two models have many significant differences in how they handle the various physical parameterizations. As a result, output products also differ, sometimes very significantly. The forecaster must then use his knowledge and experience to decide which model has the higher probability of being correct for the given circumstances.

Each centre puts out a quantitative precipitation forecast (QPF) map for 12 hour periods up to 48 hours into the future based on the physics of the model atmosphere. Forecasts are prepared out to 120 hours by the spectral model but not distributed. Both the LFM and Spectral models attempt to account for convective precipitation but only in a gross sense. A sample of the output from the two models as given by AES (1982) is included as Appendix 1 to this paper. The QPF maps are frequently not as good as this case study would indicate.

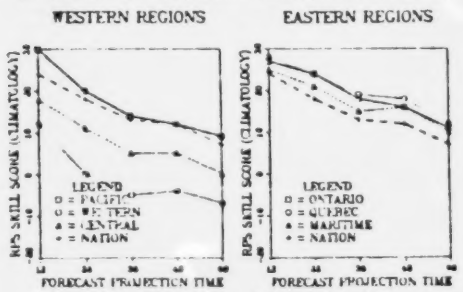
The frequency bias statistics for the Canadian Spectral model as presented by AES (1982) are informative. When all forecast times are averaged, it is found that the model contains no bias with respect to its forecasting of precipitation occurrence. The total number of times precipitation was forecast for the 74 stations is almost exactly equal to the number of times precipitation was observed. But this was the net result of forecasting precipitation too often in the first 12-h and too infrequently in the subsequent three 12-h periods.

The right hand side of Figure 2 looks at the bias when precipitation is broken down into three ranges of amount. In the lighter range (less than 10 mm per 12-h), there is overforecasting, while the heavier ranges (over 10 mm per 12-h), are forecast much too infrequently. Because the number of occurrences in the lighter category is much greater, the overall bias averages out. There is a suggestion from this graph, that while the model forecasts precipitation with the correct frequency, it underforecasts the amount of precipitation. It certainly fails to forecast the heavier precipitation events often enough. This has serious implications for streamflow forecasting. The patterns in synoptic situations, however, are reasonable.

FREQUENCY BIASES



RPS SKILL SCORES WRT CLIMATOLOGY FOR 1981 POP FORECASTS VALID 00 TO 12 GMT.



Mean ranked probability skill score as a function of forecast projection time for all 1981 POPA forecasts valid 00 to 12 GMT. Forecasts for the first three periods are by MDA and for the last 2 periods are by REEP.

In addition to the physically based QPF maps, CMC issues precipitation forecasts based upon statistically developed relationships. The relationships are developed using observed meteorological parameters and observed occurrences of precipitation. The output from the Spectral model is assumed to be a perfect predictor of the meteorological parameters in the statistical relationship and the relationships are used to estimate the probability of precipitation.

The probability of precipitation amount (POPA) forecasts are produced twice daily for five consecutive 12 hour periods. The probability of precipitation is given for three ranges, .2 to 2 mm, 2 to 10 mm and greater than 10 mm. The sum of the three forecasts gives the probability of occurrence of precipitation. These forecasts are prepared for seventy-two stations. The forecast output for the first three periods is based on a multiple discriminant analysis (MDA) technique which often shows high resolution in the forecasts. The last two forecasts are based on a regression estimate of event probability (REEP) system which is much more conservative and less discriminating than the MDA forecasts.

Verification of the POPA forecasts are presented by Wilson and Stanski (1983). The skill of the forecasts was measured using skill scores and a sample of POPA results is shown in Figure 3. The skill score measures the percent improvement of the forecast over the standard forecast which in this case was climatology. POPA forecasts ranged from 24% better than climatology for a 12 hour forecast to only 8% better than climatology for a 60 hour forecast.

Probability of precipitation forecasts are produced for days 3 to 5 using analog techniques. A search is made through 14 years of 1000 and 500 mb historical charts to find the twenty best analogs to match each of the 60, 84 and 108 hour spectral prognoses over various windows over Canada. The frequency of occurrence of precipitation on these 20 dates is taken as the POP forecast. These forecasts are issued at 00Z for a set of 93 stations giving the probability of precipitation above a trace.

Verification shows acceptable skill for day 3 and marginal skill for day 5 as shown in Table 3.

TABLE 3

Verification of Probability of Precipitation Forecasts at 93 stations (April to June 1983)

Day 3	Day 4	Day 5
12	6	3

As noted earlier the statistical relationships are derived based upon actual observations and the forecast is made assuming that the spectral model output is a perfect representation of the future state of the atmosphere. A serious problem with this "perfect prog" approach is that it does not account for consistent errors and uncertainty in the model output. The model output statistics (MOS) technique avoids this problem by developing statistical relationships directly between historical model output and observed precipitation.

CMC is developing a MOS system to produce probability of precipitation forecasts for six consecutive 12 hour periods. Testing of the MOS forecasts began in October 1982. These forecasts give the probability of measurable precipitation.

Table 4 shows comparative verifications between the MOS, forecasts and those produced using MDA and REEP (Linear regression) techniques. The latter two techniques were developed using "perfect prog" data. The verification score is the percentage improvement over climatology. Forecasts issued at 00Z for five consecutive 12 hour periods were verified for fifty stations.

The MOS forecasts showed considerable improvement over the other techniques. The MOS regression equations were developed using the output of the CMC spectral model V8. The operational model was changed on May 1, 1983 to Version 9. Using the output of Version 9 did not noticeably affect the performance of the MOS equations.

Regression equations are now being developed for the winter season using three years of historical data to give probability of precipitation for amounts greater than a trace, 2 mm and 10 mm. These equations will be tested in the coming season.

TABLE 4

Verification of Probability of Precipitation Forecasts
for 50 Stations (Oct. 1982 - June 1983)
Percent Improvement Over Climatology

PERIOD	1	2	3	4	5
MOS	39	34	34	23	20
MDA	33*	18*	22*	12	13
REEP	33	22	25	17*	17*

*Indicates forecasts currently transmitted

Obviously someone with meteorological training and experience is required to sort out the numerous numerical guidance products, assess their relative strengths and weaknesses, modify where necessary and keep abreast of new products. Ideally, each stream flow forecast office would have a meteorologist plus access to all the guidance material. Since this is not usually practical, close cooperation between the weather and flow forecast offices should be considered essential. A tailored forecast based upon the full knowledge of both the meteorological guidance and the hydrological requirements is the desired goal.

5. Application of Meteorological Information

There are two serious problems in the use of meteorological information for flow forecasting:

1. The spatial resolution of the information is often less than that required by the hydrological model.

2. The skill of forecasts decreases quite quickly with time.

The real-time observational network is usually much less dense than the climatological network used for calibration. The core of this network is the set of synoptic stations, usually located at airports and manned around the clock by salaried observers of the federal meteorological service. Although the quality and frequency of these observations is high, the density is low compared to the number of watersheds for which areal meteorological values are needed. This often dictates the use of stations located outside the basin boundary in order to provide useful information regarding the spatial distribution of a field over the entire basin. Remote sensing data from radar and satellites can often be of great assistance in interpolating between stations.

Further compromises are required when the forecast field is considered. Current dynamical forecasts of circulation patterns and fields such as temperature, moisture, vertical velocity and precipitation are produced at grid points on a continental scale. The model's horizontal and vertical resolution depend on the density of the observations - primarily the upper air network of radiosondes released at twelve hour intervals around the hemisphere - and the storage capacity and speed of the operational computer. Present day observations limit the model to an effective grid point separation of 290 km

with a forecast time step of twenty minutes. The effect of this spatial resolution on the forecast fields is to produce values of temperature and precipitation representative of grid squares 300 km to a side. In a basin as large as the Ottawa Basin there are only six of these grid squares.

The deterioration of forecast skill with time forces a greater reliance on climatology, particularly for forecasts beyond three days. This is especially true with precipitation forecasts where the skill in forecasting precipitation amounts is minimal after 36 or 48 hours. Beyond this time, skill is evident only in the forecast occurrence of daily precipitation, expressed as a probability. Pugsley (1977) has suggested a way to apply the probability of precipitation forecast for days 3, 4 and 5 to yield quantitative estimates of rain. The forecasts are first categorized as 1 or 0, for precipitation occurrence or not - using 50% as a threshold. All forecasts of 1 were then assigned a precipitation amount derived from the mean rainfall experienced historically on a day with rain at that location. Rain day statistics were used instead of the more general precipitation values (snow and rain combined) because rain alone will be observed as runoff in the short term.

6. Tomorrow's Operational Tools

It is probably safe to assume that technological change will continue to dazzle us for the next decade. It is even safer to assume that advances in operational meteorology and hydrology will be limited by resources and our knowledge and ability to take advantage of advances that have already taken place.

DCP's and other automatic observing installations will continue to proliferate making more surface data accessible, especially from remote regions. In fact, it is not inconceivable that data from remote areas might be more readily accessible in real-time than that from populated areas where human observation is involved. High quality radar and satellite data covering much of Canada is already being collected and systems to facilitate access to these data should be in place in the next few years. In the longer term, passive and active microwave sensors aboard satellites may provide improved information on snow cover parameters and precipitation.

All this means more but different data available. How will it all be effectively handled? Improved communication systems will be essential to move high volume remote sensing data. AES is already acquiring elements of the badly needed new communication system (NCS) scheduled to be fully implemented by the late 1980's. This is a long looked for improvement for AES but it may aggravate rather than alleviate users problems in some ways by adding to the volume of data available and changing the methods of communication, with resultant cost implications.

Once the data are distributed, processing systems and software must be developed, both within AES and by users, to handle new data formats and quality, and to do things like integrate remotely sensed data into applications systems developed for conventional data. Within AES the new super-computer Cray 1S (to be installed before the end of 1983) will be

integrating conventional and new data forms into more complex models of the atmosphere with the aim of improving and extending forecasts. Realistic expectations for the new system include:

1985-86 - extension of significant forecast skill into Day 6 of the forecast period.

- a reduction in the errors in temperature forecasts.

1986-87 - incorporation into the operational runs of a regional model (finite element model) will provide more detailed treatment of weather conditions in the first 48 hours of the forecast period.

- automated prediction of all weather elements (more and better guidance).

- better accuracy in the prediction of precipitation amounts especially for the larger amounts associated with smaller-scale, severe, weather systems.

- improved wind forecasts (in particular, better detail for critical marine wind and wave forecasts).

- substantially-increased volume of forecasts for specific localities, and for the locations of events exceeding specified limits, available for "core" forecasting and for users who wish to come and get the information.

1987-88 - global model, introduced in 1986 or 1987, will extend the range of skillful forecasts beyond 7 days for all Canadian territory (a further 20% improvement).

The vector computer will also result in improvements in the evaluation of climate-change possibilities, seasonal forecasts with skill (1995), quantitative evaluations of the long-range transport of pollutants, and the progress of university research in several atmospheric and oceanic subjects.

7. Conclusions

Meteorological support to flow forecasting is required and has been demonstrated across Canada. Various combinations of observations, special analyses and tailored forecasts are made available by AES offices. Allowances must be made for the relatively low spatial resolution of meteorological observations and forecast models. Various numerical guidance material does show skill out to day 5 in the precipitation and temperature forecasts but the skill decreases with time and the material is best interpreted by personnel with meteorological expertise.

Developments within AES will make new data from DCP's, radar and satellites available but users will have to make major adjustments in how the new type of data are manipulated and integrated into existing flow forecast models and techniques. The new AES vector computer is expected to improve

temperature and precipitation forecasts in both quality and resolution. The valid period will be extended beyond a week by the late 1980's and seasonal forecasts with skill are expected by 1995.

From the meteorologist's point of view, there are still numerous questions to be answered concerning the application of meteorology to streamflow forecasting. It seems appropriate to close this paper by listing some of these questions with the aim of stimulating discussion at the workshop and afterward. The questions include:

In order of priority, what are the meteorological parameters required for streamflow forecasting?

Quantitatively, what are the spatial and temporal resolution requirements for meteorological parameters?

What are the impacts of not meeting these requirements?

What is the sensitivity of hydrological model output to meteorological input?

Can hydrological flow models take advantage of improved quantitative meteorological information if it becomes available or will the improvement be lost in calibration constants and other fudge factors (optimization routines)?

Does the lumped nature of most hydrological flow models currently used in Canada make them inappropriate for use with present and future remote sensing data which is strong on spatial distribution information?

Are there new hydrological flow models which address some of these problems?

There are almost certainly as many or more questions that the streamflow forecaster has for the meteorologist.

8. Acknowledgement

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Appendix 1
QPF Case Study

CASE 2 - 12Z 10 JULY 1982

Synoptic Situation

A polar cold front from Minnesota to northern Texas is drifting eastward. A weak wave near Topeka is progressing northeastward along the front. The Maritime tropical airmass is quite unstable.

Progs

Both the Spectral and the LFM progs have reasonable surface patterns. Although neither specifically has the wave, both models have an area of PVA in an appropriate position.

Precipitation

The precipitation in this case was largely the result of convection triggered by the wave (or PVA). The precipitation amounts were quite variable within a reasonably small area with a maximum of 83.8 mm observed at one station.

The 24-h Spectral QPF forecast heavy precipitation in the proper area but in trying to handle the amounts it made the area far too large. The area appeared to be more organized than it actually was.

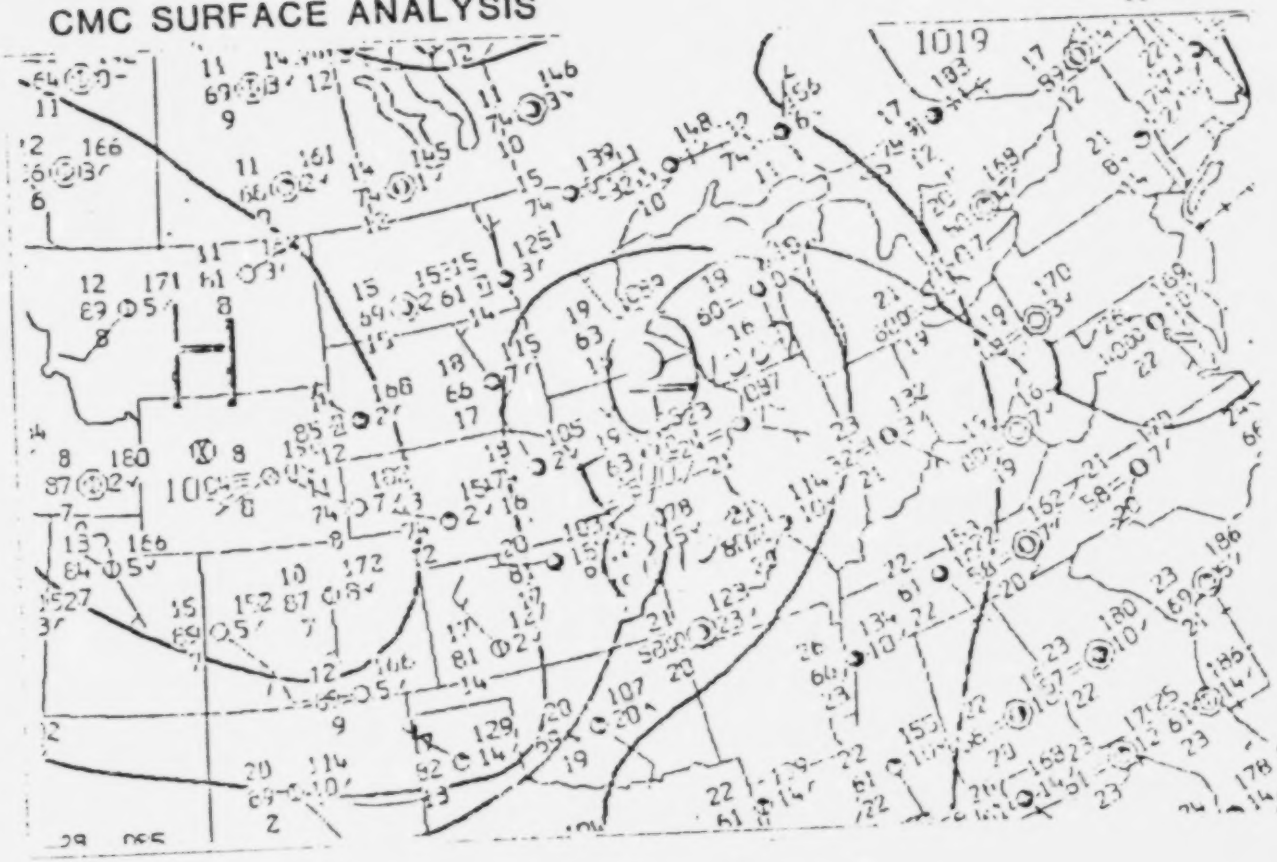
The 24-h LFM forecast a very large area of precipitation and gave no indication of the heavier precipitation.

Points Demonstrated

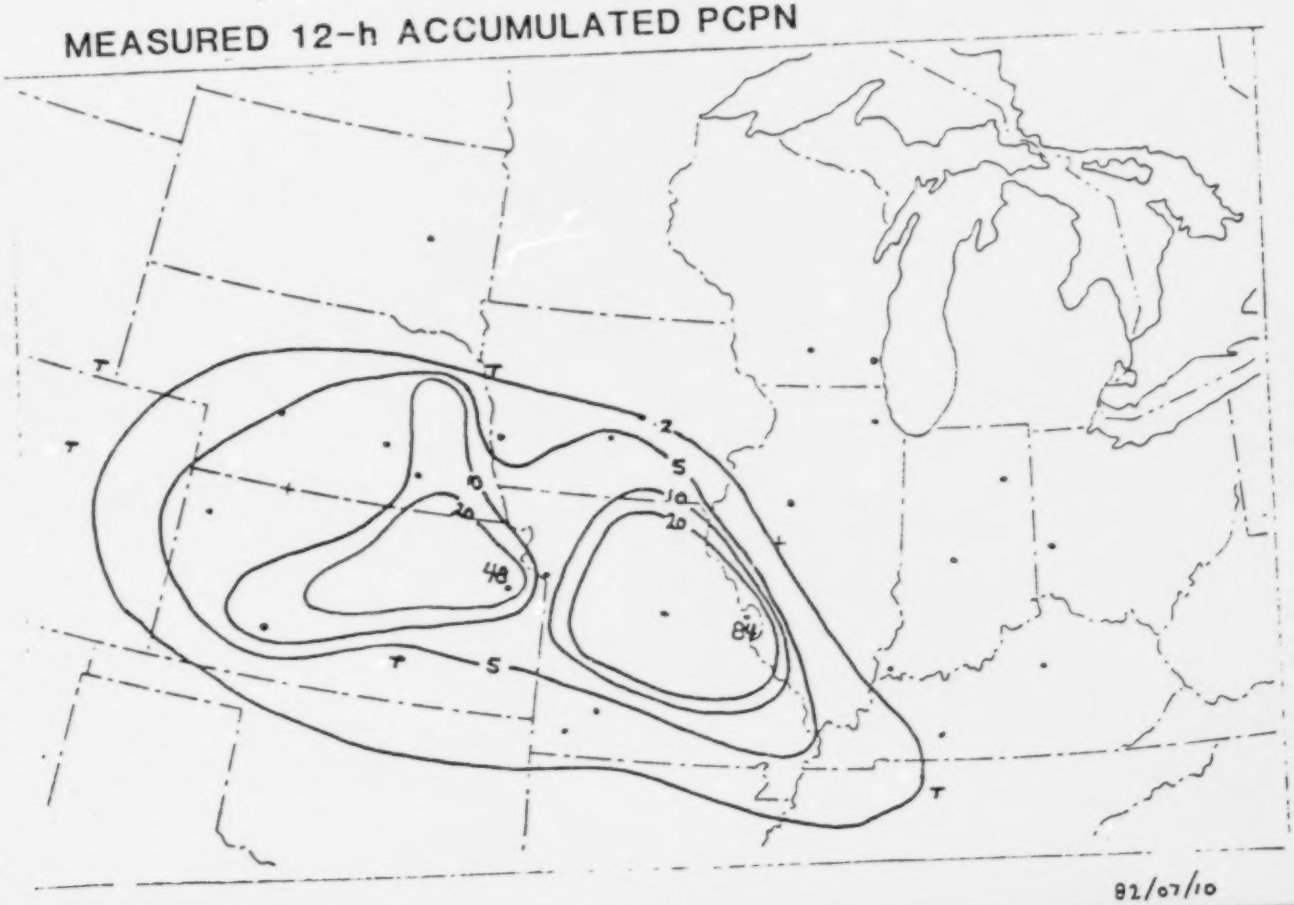
This case serves to illustrate:

- The Spectral model has a better formulation of the convective process than does the LFM.
- Both models present a precipitation pattern that is generally more organized than in reality.
- Both models compensate for heavy local precipitation by having too large a precipitation area.

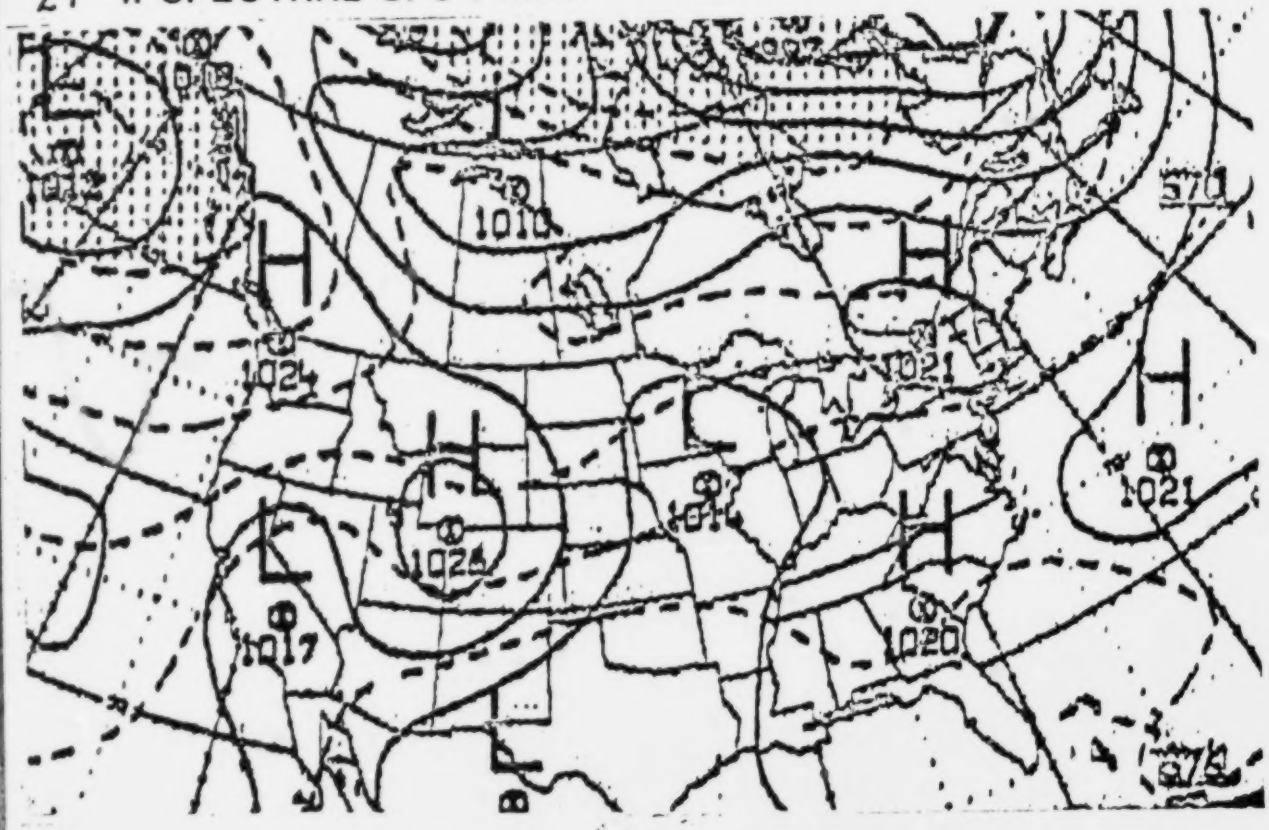
CMC SURFACE ANALYSIS



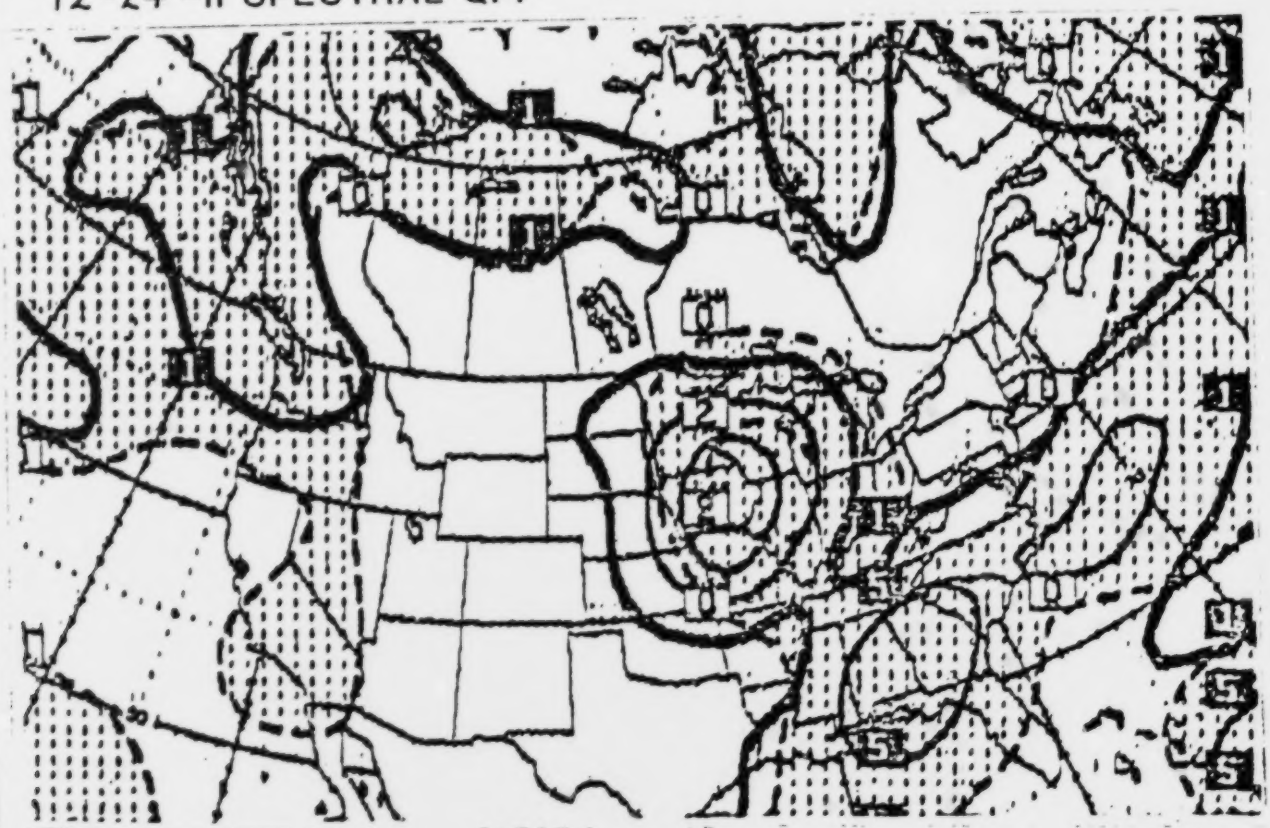
MEASURED 12-h ACCUMULATED PCPN



24 -h SPECTRAL SFC PROG



12-24 -h SPECTRAL QPF



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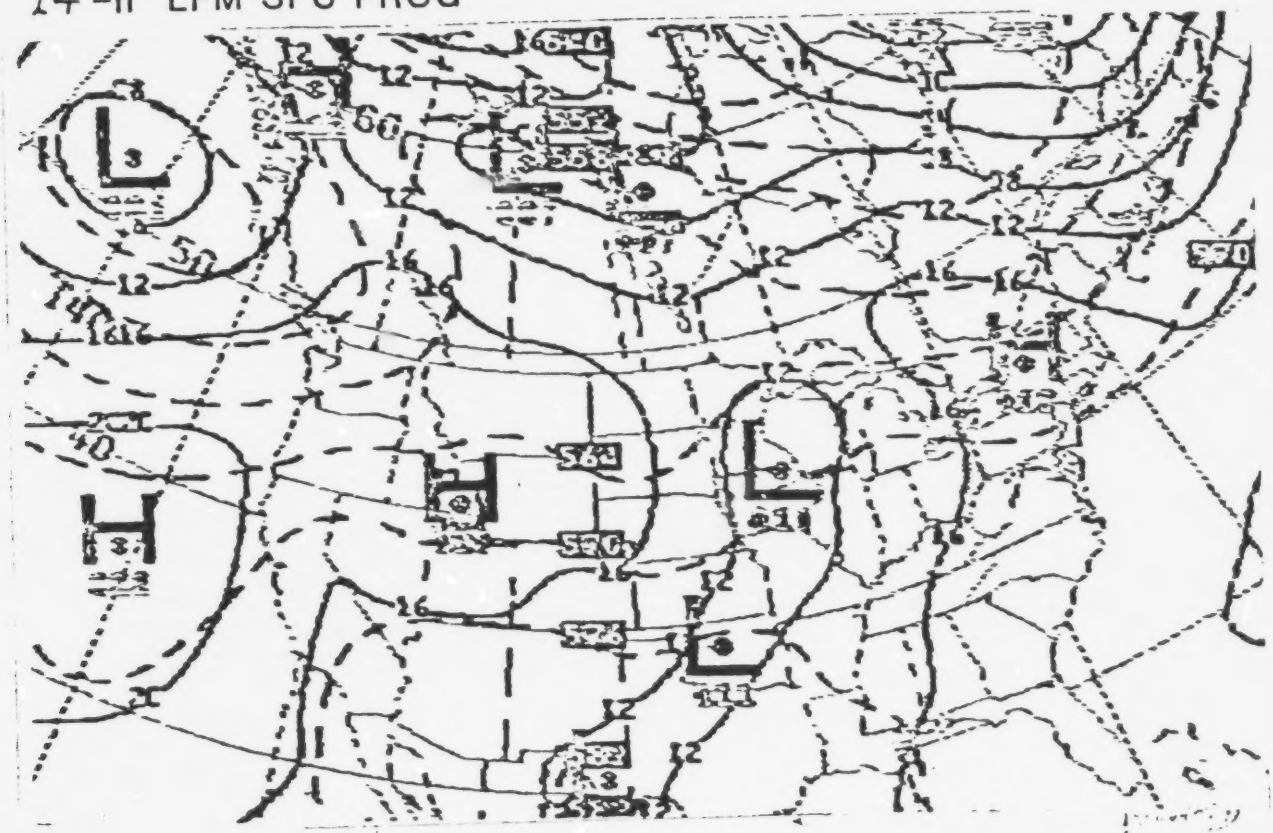
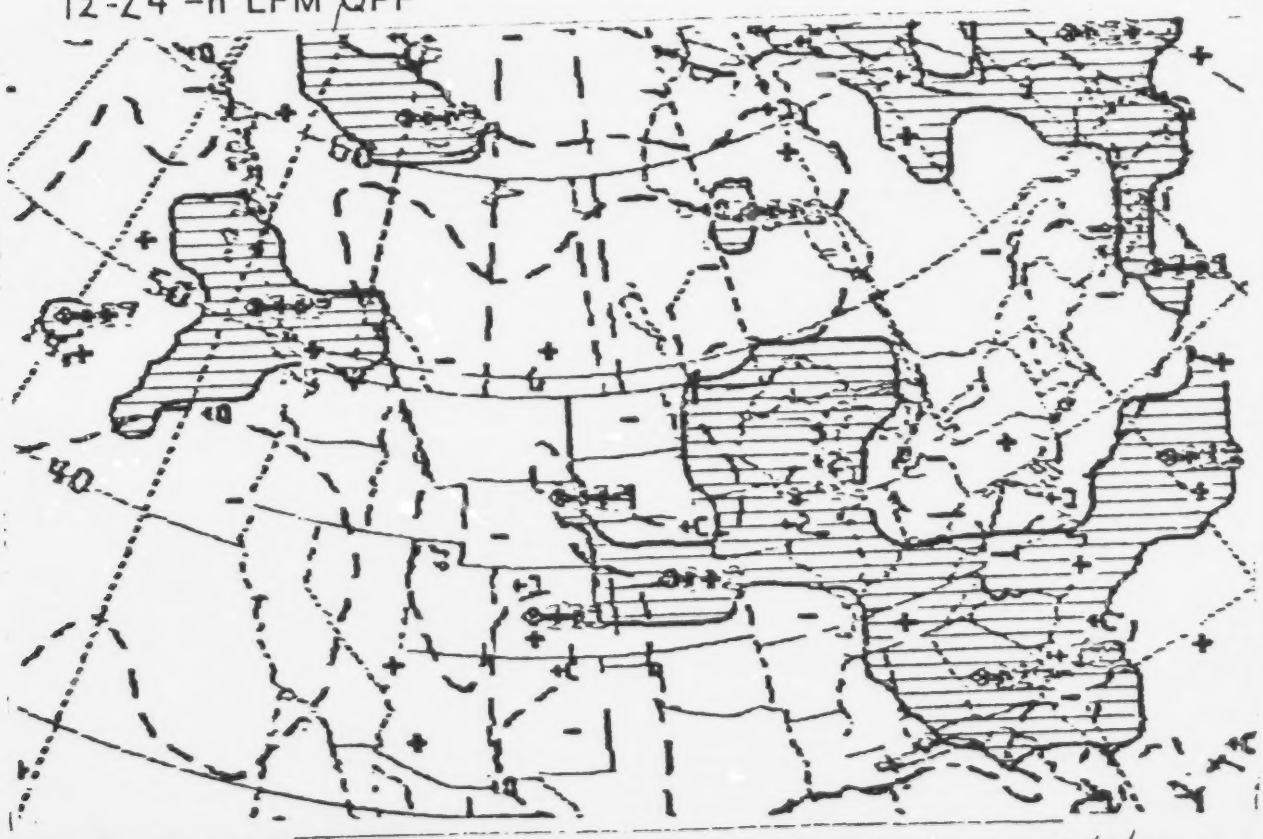
24-h LFM SFC PROG



12-24-h LFM QPF



METEOROLOGICAL SUPPORT FOR FLOOD FORECASTING IN CANADA
A Case History for the Ottawa River

by

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of

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CANADA

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METEOROLOGICAL SUPPORT FOR FLOOD FORECASTING IN CANADA
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ABSTRACT

The Atmospheric Environment Service has become increasingly involved in recent years in supplying specialized observations and forecasts to operational flood forecasters across Canada. The introduction of computer models to forecast daily river flows has brought a demand for objective long range forecasts of precipitation and temperature on a scale not previously required or available.

This paper reviews meteorological procedures, data manipulation, and forecast techniques employed in the development of a streamflow forecast model for the Ottawa River Basin. Verification of meteorological elements from the 1976 and 1977 spring demonstration periods is presented. The precision of the forecasts in time and in space is indicated.

METEOROLOGICAL SUPPORT FOR FLOOD FORECASTING IN CANADA
A Case History for the Ottawa River

W.I. Pugsley[1]

INTRODUCTION

The advent of mathematical models for streamflow forecasting in Canada has brought with it a demand for precise meteorological observations and long range forecasts as well as a need for rapid transmission of these data in computer readable form. Since 1970 the Atmospheric Environment Service has provided dedicated and specialized support for the implementation of several major flood forecasting systems including:

a) the Saskatchewan River Basin under the aegis of the Prairie Provinces Water Board,
b) the Saint John River Basin under the aegis of the World Meteorological Organization pilot study to assess the application of World Weather Watch to operational hydrology,
c) the Ottawa River Basin under the aegis of the federal-provincial Committee on Flow Regulation.

As a result of the close liaison between the model developers and the meteorologists from the moment of its conception, the Ottawa River flow forecasting project serves as an appropriate and recent example from which to describe and assess the role of meteorological support through the model's development:

a) the gathering of a historical data base for calibration,
b) the design of a real-time observational and forecast network,
c) the transmission of meteorological data, and
d) the quality control of observations and the verification of forecasts.

Following a summary of particular aspects of the Ottawa Basin study, a review is made below of the more general meteorological considerations required in designing networks, transmitting data, and assessing the skill of forecasts in support of flood forecasting

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THE OTTAWA RIVER FLOW FORECASTING PROJECT - A SYNOPSIS

In June 1975 the Atmospheric Environment Service was asked to provide meteorological support for the development of a daily flow forecasting model for the Ottawa River. The requirement came from the inter-departmental Comm'ttee on Flow Regulation, Montreal Region which has representatives from the federal government as well as from the provincial governments and hydroelectric agencies of Ontario and Quebec. The objective of the project was to demonstrate the feasibility of a real-time forecasting capability to improve flood protection and to enhance hydroelectric energy benefits throughout the basin.

The Ottawa River is 1,272 km long with a mean annual discharge of 1,953 m^3/s. There are twenty one reservoirs and thirty seven power plants in the basin. About two-thirds of the total drainage area (145,040 km^2) lies in Quebec with the remainder in Ontario. Val d'Or lies on the northern boundary of the area, Chapleau to the northwest, Roberval to the east, and Kingston and Montreal to the southeast. For the purpose of the model demonstrations in the spring of 1976 and again in 1977, the area was divided into forty two watersheds of which thirty two were calibrated and ranged in size from 62 km^2 to 13,000 km^2. Daily observations of temperatureand precipitation from 147 climatological stations over a period of nineteen years were compiled on magnetic tape to form the historical meteorological data base. Of this total, 57 stations were selected later as calibration points. Of these, only 19 stations provide observations in real-time.

The following meteorological services were provided during the development and testing of the model:

a) specification of monthly mean potential evaporation values for each watershed for the determination of a model soil moisture index for separating surface from sub-surface flows;
b) selection and provision of historical data for calibration of the model during selected flood events;
c) development of a way to provide meteorological data in computer compatible form at each calibration point for up to five days in advance in real-time;
d) operational provision of the above data for each day of the demonstration period each year, i.e. from March 1 to May 31.

THE METEOROLOGICAL NETWORK

The requirements for meteorological data can be divided into three networks, each associated with a particular application in the development and testing of the operational flow forecast model:

a) the network used for calibration,
b) the network used to assess the observed meteorological fields in real-time,

c) the network used to describe the forecast meteorological fields.

For calibration, the primary objective is to amass a data bank from which a set of flood events can be chosen. These data are made up of virtually all meteorological observations, both climatological and those available in real-time. In the case of the Ottawa Basin, daily values of temperature and precipitation for 147 stations over a nineteen year period were compiled on twenty seven magnetic tapes to form the historical data base. At this point the hydrologist, with an eye to the hydrometric data base, selects the particular years when significant flood events occurred, and the particular meteorological stations to be used for calibrating the individual watersheds. The initial data base was thus reduced to 57 stations for seven flood years. Out of these, three spring periods were selected for calibration, leaving the remainder to be used as independent data to later test the calibrated model.

The real-time observational network is usually much less dense than the network used for calibration. The core of this network is the set of synoptic stations, usually located at airports and manned around the clock by salaried observers of the federal meteorological service. Although the quality and frequency of these observations is high, the density is low compared to the number of watersheds for which areal meteorological values are needed. This often dictates the use of stations located outside the basin boundary in order to provide useful information regarding the spatial distribution of a field over the entire basin. As shown in Figure 1, only nineteen stations take observations in real-time. Remote stations such as Moosonee and Roberval were included to give data in the north and northeast, where a dense network within the basin does not exist. Another consideration in selecting the real-time network is to provide for back-ups when observations are garbled or missing during transmission.

Further compromises are required when the forecast field is considered; these become more critical as the length of the forecast period increases. Forecasts of temperature and precipitation for the first day or two present few problems in terms of skill or availability, as will be discussed below. The major difficulty is the spatial resolution of the meteorological forecast model. Current dynamical forecasts of circulation patterns and fields such as temperature, moisture, and vertical velocity are produced at grid points on a continental scale. The model's horizontal and vertical resolution depend on the density of the observations - primarily the upper air network of radiosondes released at twelve hour intervals around the hemisphere - and the storage capacity and speed of the operational computer. Present day technology limits the model to an effective grid point separation of 190.5 km with a forecast time step of about one hour. The effect of this spatial resolution on the forecast fields is to produce values of temperature and precipitation representative of grid squares 200 km to a side. In the Ottawa Basin there are only six of these grid squares.

The deterioration of forecast skill with time forces a greater reliance on climatology, particularly for forecasts beyond three days. This is especially true with precipitation forecasts where the skill in forecasting precipitation amounts is minimal after 36 or 48 hr. Beyond this time, skill is evident only in the forecast occurrence of daily precipitation, usually expressed as a probability. In the application of probability forecasts for days 3,4 and 5 for this project, the forecasts were first categorized as 1 or 0, for precipitation occurrence or not - using 50% as a threshold. All forecasts of 1 were then assigned a precipitation amount derived from the mean rainfall experienced historically on a day with rain at that location. Rain day statistics were used instead of the more general precipitation values (snow and rain combined) because rain alone will be observed as runoff in the short term. Although the number of rain days per month increases during the spring along with warmer temperatures, the rainfall amount that falls on each day increases quite slowly from 4.6 mm in March to 5.6 mm in May when averaged over the basin. Individual stations receive as little as 2.5 mm in March to as much as 6.4 mm per rain day in May based on their period of record. The forecast information consisted then of forecast values of mean temperature and precipitation amount for each day for five days ahead at six points. As the operational meteorological model is a spectral model, fixed grid points were not used;rather, suitable forecast points were specified by their latitude and longitude alone.

TRANSMISSION OF METEOROLOGICAL DATA

The format, content, and mode of transmision of observations and forecasts depend on the following:

a) the time of observation,
b) the issue times of the forecasts,
c) the turn around time of the flood forecast model,
d) the required time for dissemination of the flood warning.

Although observations are made hourly or more often at synoptic (aviation) stations, precipitation amounts are observed only at three or six hourly intervals. Forecasts are based on hemispheric observations made at twelve hour intervals - in the early evening and early morning in eastern Canada (midnight and noon Greenwich Mean Time, respectively). Because of the required processing time, raw forecasts of precipitation and temperature are not available from the model for two or three hours. The final forecasts, refined and massaged by regional forecasters, are made available after a further one hour. This means that forecasts based on observations made, for example, at 7 A.M. are not normally available until noon. Similarly, evening forecasts are not normally available until midnight local time.

The timing of the computer run of the hydrological forecast model depends to a large extent on the required hour for forecast dissemination to concerned users, and the turn around time for the computer to

make the forecasts - say, two hours. Normally a flood forecast is desired each day by early afternoon. This in turn requires that all input data, including meteorological observations and forecasts, be assembled and compiled in machine readable form by 9 A.M. or 10 A.M. In some regions of Canada, and in the Ottawa Basin in particular, this schedule dictates the use of forecasts based on data twelve to fourteen hours old. The most recent observations, on the other hand, are no more than three to six hours old relative to the flood forecast release time.

When a meteorological forecaster is not physically located in the flood forecast centre, a means of communication must be provided to transfer data - in the case of this project, over a distance of over 150 km. As little delay as possible should take place between the preparation of the meteorological forecast and its use in forecasting flows. This requirement for rapid transfer of detailed information, preferably in a form suitable for immediate use as computer input, narrows the choice of alternatives. An optimum system would transfer observations and forecasts directly from the meteorological computer to the hydrological computer. An obvious consideration is cost. One must weigh the benefits of including supplementary information for quality control or back-up against the cost of a longer message and transmission time.

In the Ottawa Basin project, two transmission techniques were employed. In the spring of 1976, a new regional computer had arrived too late at the weather office to be used directly in this project. As a result, observations for nineteen stations and forecasts for six points were punched manually on paper tape and retransmitted each day directly into the storage area of the flood forecast computer in Hull. Although only the six-hourly values of precipitation were needed, the daily total was also transmitted as a check. The message was made up of twenty five lines of data, each containing up to eleven pieces of information. During the demonstration period, it became evident that the two or three inevitable punching errors on each message prevented its immediate use in the computer model. Eventually, after the conclusion of the demonstration period, these errors were eliminated by a visual examination and some consistency checks from listings of the stored data. The majority of these problems arose from retransmission of the observations rather than in the forecasts themselves which were prepared in Montreal. In 1977 a telecopier was introduced at the weather office whereby the complete message prepared by the forecaster in a format suitable for key punching was transmitted in hard copy to Hull. Only a quick visual examination by a technician familiar with the message content was necessary before putting these data into the computer. Two obvious but important lessons were learned from this experience:

a) it is quite difficult and time-consuming to detect and remove errors after they find their way on to the computer files;
b) there is a definite need to check the data ,visually at least, before they are read operationally by the flood forecast computer. Any discrepancies can be detected and eliminated by a telephone call to the weather office which has secondary aids such as precipitation radar and hour-by-hour reports from the synoptic network at hand.

One way of avoiding data transmission problems is to largely eliminate them by collocating the flood forecasters in the weather forecast office, as is done in the National Weather Service of the United States.

QUALITY CONTROL AND VERIFICATION

Quality control must take place at all stages of the process from the moment an observation is taken to the point where hundreds of observations are analyzed and forecasts produced at the weather office, to the final stage where selected data are read as meteorological input into the flood forecast model. Because of the short time available in the real-time world - usually two hours, a combination of systematic computer checks and subjective manual interventions are employed. After the event, a thorough examination of both the observations and forecasts is necessary :

a) to identify systematic forecast errors or biases, perhaps due to local conditions, that indicate the need for last minute subjective adjustments;
b) to evaluate the observational network to identify gaps or persisting errors at particular stations (see Mapanao and Pugsley, 1977);
c) to further improve the forecast technique or at least to be aware of its drawbacks.

Forecast Techniques

The basic guidance and objective meteorological forecasts in Canada originate from the Canadian Meteorological Centre in Montreal. Quantitative precipitation forecasts have been produced for all of Canada since early 1968 for up to 36 hr ahead. Davies and Olson (1973) have described the evolution of the forecast technique with special reference to the problem of the scale of precipitation events. As precipitation rate is derived from a dynamical model of the northern hemisphere at grid points about 200 km apart, the spatial resolution of the forecast precipitation field cannot exceed this without a further adjustment. Extraplation of finer scale features using more detailed observations from weather radar, satellite photographs, and the documented continuity of synoptic features in time and space improves the skill of point forecasts of precipitation in the first 12 to 18 hr. This latter adjustment takes place at regional forecast offices such as the Quebec Forecast Office at Montreal. Since the spring of 1976, objective forecasts of daily precipitation and temperature extremes for up to five days ahead have been issued operationally with the same resolution as for the shorter range forecasts of precipitation amount. By associating the probability above a given threshold with the mostlikely amount climatologically, long range forecasts of precipitation amounts were produced for flood forecasting in the Ottawa Basin.

Objective forecasts of temperature extremes have been produced for Canadian first order stations since the fall of 1969 for up to

60 hr in advance. As noted above, the forecast period was extended to five days in 1976. For the estimate of snowmelt in the Ottawa Basin, only the forecast daily mean temperature was used. Although the spatial resolution of temperature forecasts is the same as for the precipitation, subjective adjustments can be made to improve the forecasts in the first two days by incorporating such parameters as cloud cover and precipitation occurrence as described by Pugsley(1971).

The Data Base for Verification

The data used in this analysis consisted of the observations and forecasts as received at the flood forecasting centre in Hull during the period March 1 to May 25, 1976 and from March 1-25, 1977. Each morning the following observations for each of the nineteen synoptic stations were transmitted:

(a) precipitation amount for each 6 hr period in the 24 hr period up to that morning,
(b) 24 hr precipitation amount
(c) maximum and minimum temperature extremes in the 24 hr period up to the preceding midnight.

Forecasts for each of the six forecast points consisted of:

(a) daily mean temperature for days 1, 2, 3, 4 and 5
(b) 12 hr precipitation amounts for day 1
(c) precipitation probability (1 or 0) for days 2, 3, 4 and 5.

Although the probability of precipitation was transformed to an amount at each of the 57 calibration points as final input to the flood forecast, for ease of computation, verification was performed only on the 19 synoptic stations.

Verification Method

The primary objective was to determine the utility of precipitation forecasts at a point and for the basin as a whole. It is recognized that the value needed is not at a point but over a watershed. In addition, the inherent limitation of the meteorological model to resolve features smaller than 40,000 km^2 especially beyond two days led to an emphasis on basin mean daily values. Error analyses were performed on a monthly basis from an examination of the frequency of daily errors within each increment of the indicated range. From this and calculations of bias and average absolute error, the error summaries present the typical error to be expected as well as the proportion of errors within an operationally tolerable limit. With reference to Table 1, the following additional comments are noted for each element.

(a) Point precipitation event forecasts - the "percentage of correct forecasts" is the percentage of the wet and dry days correctly forecast out of the total, where amounts greater than 2 mm/day or probability forecasts equal to 1 constituted a precipitation event. Threat scores computed from contingency tables present the portion of threatening situations correctly forecast, i.e. the percentage of wet days correctly forecast out of the number of days on which precipitation was observed or forecast. As demonstrated by Davies (1975) the

threat score for day 1 decreases from 55% for a threshold of 2 mm/day to 13% for a threshold of 25 mm/day.

(b) Basin precipitation amount forecasts - forecasts of amount for the first day and of probability averaged and converted to amount for each of the next four days were compared to the average observed amount at the nineteen synoptic stations.

(c) Point temperature forecasts - only one station (Ottawa) was chosen for comparison with basin values and previous verification studies. Monthly values of root mean square error were also computed.

(d) Basin temperature forecasts - the average of the six point forecasts was compared to the average of the nineteen observations.

(e) Basin snowmelt forecasts - as a refinement of the temperature analysis, daily snowmelt errors were computed from the familiar degree day equation with a melt constant of 2.3 mm/deg. C (or .05 in/deg. F). In terms of error, the base temperature does not appear. The use of an uncalibrated melt constant is intended only to indicate the general consequence of temperature errors on snowmelt. As all snow in the basin had melted by the end of April both years, May 1976 was excluded from this analysis.

Discussion of Results

(a) Precipitation. More than 60% of all event forecasts were correct for the first four days in three out of the four months, and above chance (50%) for all days except days 4 and 5 in March 1976. The threat scores for day 1 were slightly higher than those computed by Davies from the spring of 1973 from all stations in North America. Except for day 5, more than a third of all threatening situations were correctly forecast.

Turning to the basin amount errors, the second element in Table 1, the mean absolute error was less than 3 mm/day for all five days. The average error or bias was less than 2 mm/day. More than 50% of all forecasts were correct to within 2.5 mm/day except for May 1976 and day 5 of March 1976. The poorer results of May (38 to 69% within 2.5 mm) reflect the greater variability of convective precipitation in late spring. More than 80% of forecast errors were less than 5.1 mm/day on all five days and for all four months.

(b) Temperature. The mean absolute error of the forecasts for Ottawa were 0.5 to 1.0 deg. C smaller than those computed for the same station in 1970 by Pugsley (1971), indicating a possible improvement in the forecast techniques over the years. More than 50% of the forecasts were within 2 deg. C of the observed values on days 1 and 2, and within 4 deg. C beyond day 2. The bias was smaller than 1 deg. C on days 1 and 2 but increased to 4 deg. C on day 5.

In comparison, the basin mean forecast errors indicate a slightly greater precision, particularly on day 1 when over 80% of the errors were less than 2 deg. C. The larger errors for March 1977 for forecasts beyond two days (absolute error, 3 to 6 deg. C) indicates the forecast difficulty in a month when there were six periods alternating above and below the freezing point. Even in this month 40% of the errors were less than 4 deg. C.

(c) Snowmelt. Although only 35 days in the three months were above freezing, the last lines in Table 1 indicate the reliability of using temperature forecasts to estimate basin snowmelt. During the two March periods, the mean absolute error was less than 2 mm/day, and over two thirds of the errors were less than 5 mm/day out to day 4. Over 85% of the errors were less than 10 mm/day in all three months. It should be noted that typical snowmelt errors were less than typical precipitation errors on day 1 or day 2 but exceeded or equalled precipitation errors on days 3, 4 and 5.

At the flood forecast centre, the calibrated version of the model was not received until after the 1976 peak flow. Most of the flood events selected for calibration occurred in late May whereas the 1976 flood appeared in early April. Verification of forecast flows showed reasonably good agreement with observed values even as far ahead as seven days (see Brown, 1977). For example, the mean absolute error at Carillon in the lower basin ranged from 6% on day 1 to 14% on day 7. Early indications from the flow forecasts for 1977 indicate a continuation of reliable forecasts.

CONCLUSIONS

Three years of meteorological support for flood forecasting in the Ottawa Basin have indicated the measurable benefits of a system of networks, data transfer and specialized forecasts to the final hydrological forecast. The drop off in meteorological forecast skill beyond day 2 was reflected in errors of the timing of peak flows rather than magnitude as shown by Brown (1977). This result was anticipated from the negligible bias in precipitation forecasts for five days ahead and for temperature forecasts for three days ahead.

Studies are on going to improve both the observational and forecasts to flood forecasting. Gandin's statistical technique has been used to assess the daily precipitation network in the Saint John Basin and will be applied to the Ottawa Basin in the near future. By means of liaison and consultation with hydrometeorologists through each stage in the development of a flood forecast model, hydrologists can produce reliable forecasts for longer periods than has been possible before now.

ACKNOWLEDGEMENTS

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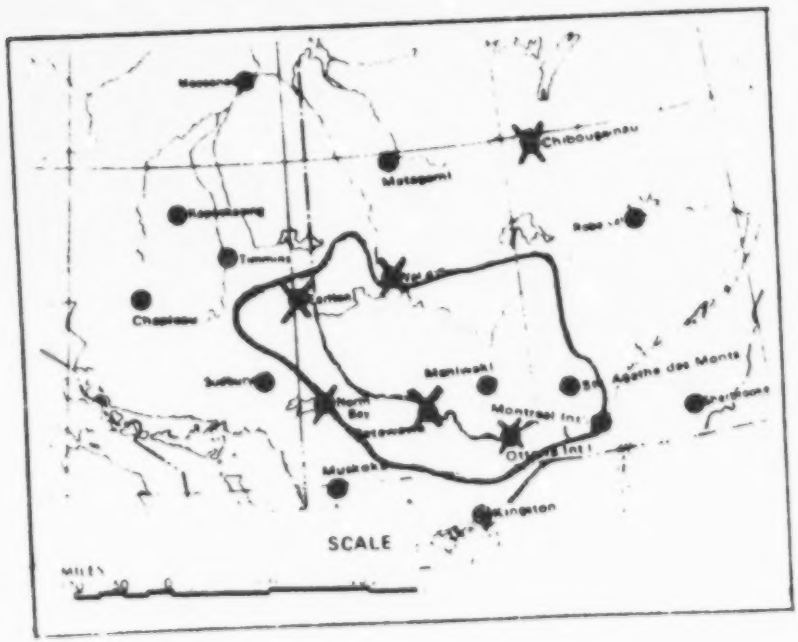

Figure 1. Map of Ottawa River Basin showing real-time meteorological observing network and forecast points (crossed circles).

Table 1 Verification of Daily Forecasts for Period March 1 to May 25, 1976 and March 1 - 30, 1976 (Number of cases shown within parentheses after % correct)

Element	Score	Day of Forecast 1	2	3	4	5
(a) Point Precipitation (all six points collectively)	% Correct (684)	70	65	63	59	52
	Threat Score - %	59	49	49	40	31
(b) Basin Precipitation	Mean Absolute Error - mm	2.2	2.5	2.7	2.5	2.8
	% Correct (111) within 2.5 mm	71	60	60	64	63
(c) Point Temperature (Ottawa)	Mean Absolute Error - deg C	1.9	2.5	3.4	4.3	4.7
	% Correct (111) within 2 deg C	64	57	40	29	32
(d) Basin Temperature	Mean Absolute Error - deg C	1.4	2.3	3.3	3.6	4.5
	% Correct (111) within 2 deg C	81	57	43	37	25
(e) Basin Snowmelt (excluding May '76)	Mean Absolute Error - mm	1.5	2.0	3.0	3.0	4.4
	% Correct (88) within 5.1 mm	88	87	73	76	62

Theme Paper

Working Group Two

HYDROMETRIC INPUT TO FORECASTING

Presented at:

AES-IWD Technical Workshop on Streamflow Forecasting

AES Headquarters, Downsview, Ontario

November 22-24, 1983

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Theme Paper - Working Group Two
Hydrometric Input to Forecasting

1. Introduction

In speaking of hydrometric input to flow forecasting, we are referring to measured water level and flow data which is available on a real-time basis. Traditionally the bulk of hydrometric data in Canada has been collected for resource inventory purposes rather than for real-time applications. This is changing as the demand for efficient management of our water resources is increasing and, simultaneously, technology in making real-time data acquisition more and more viable. In fact, virtually all level and flow data may be available in real-time in the future. In light of this shift, the Water Survey of Canada (WSC) has in recent years been involved in drafting new policies and procedures more appropriate to the operation of a real-time network. However, it has not always been possible to satisfy the needs of the data users. On the other hand, data users are at times overdemanding in their expectations and unaware of data accuracy limitations. The authors believe that, in order for the data collector to provide a timely, useful product, and to ensure that the forecaster can use the data most effectively, it is crucial that communication links be strengthened between the two groups and that each become more familiar with the role and problems of the other.

This workshop is one means of strengthening communications and initiating better understanding. It will be the purpose of this paper to provide a framework for discussion between the two groups. In Section 2 real-time data collection and transmission is briefly outlined. Section 3 identifies sources of error in data with which data users should be familiar. Section 4 identifies some needs of the data collectors and users and Section 5 makes a proposal for continued interaction between the groups.

2. Real-Time Data Collection and Transmission

It is first necessary to point out that "real-time" may imply considerably different time horizons to different people depending upon the system with which they work. To illustrate this, consider the following systems in Canada: the Great Lakes, the Lake of the Woods basin, the Grand River basin in southern Ontario and the storm sewer system of a city. In the first, the time horizon of interest to the forecaster may be many months or years; in the second it is weeks and months; in the third it is hours and days and in the fourth it is minutes and hours. In systems with significant storage and long travel times, the timeliness of the data is not normally a critical factor. However, the data may be used in seasonal forecasts of inflow volume, based on regression analysis, for which consistency in data collection techniques

over the years is very important. Also, in computing net inflows to large water bodies, the ability to accurately determine mean water level is critical. In contrast, for systems with very short response times, the timeliness of data is as important as the data itself. The data will probably be used in sophisticated routing models to determine both level and time of peak at some downstream site. The point is that, although the data collected will be the same in all instances (i.e. levels and flows), there will be significant differences in the way the data is used for forecasting and consequently in the criteria for data collection and transmission and perhaps also in the quality standards of the data. These factors should be defined and discussed between the data collector and user. The collector will need such information in order to recommend appropriate equipment and data transmission procedures. Knowledge of the importance of timeliness to the user and the impact of equipment failure will aid the data collector in scheduling field trips and in establishing priorities for when the needs of all users cannot be satisfied at once. In turn the user will be able to assess the expected reliability of data availability and to determine the need for backup or alternate procedures. Also, knowledge of how the data is to be used will permit the collector to point out limitations of the data while knowledge of data collection procedures and problems at the site in question will permit the user to assess their impact on the accuracy of his work.

Regardless of the time horizon of the system at hand, if data is to be provided in real-time, then non-standard hydrometric equipment or other special arrangements will be required. Level data may be obtained by any of the following means:

- DCP (automated on-site sampling and memory; transmission via satellite)
- DATS (automated on-site sampling and memory; transmission by land-line)
- Telemark (spot sampling at time of call; transmission by land-line)
- Verbal telephone communication - with plant operators
  - with observers

When the level data is obtained by any of the first three means, the measurement may be made by standard equipment such as a stilling well float or a servomanometer. In the case of verbal communications, a staff gauge may also be used.

Flows are normally determined from recorded levels by means of a stage-discharge relationship. Levels are obtained as noted above for input to this relationship. In the case of staffed sites such as hydroelectric stations, flows as well as levels may be obtained directly from the operators.

The significant difference in real-time systems is, of course, not how the data is measured but how it is transmitted. Verbal

communications provided the first real-time systems and are still probably the least expensive alternative. However, they are limited to sites where there are people available to talk to; this is not normally a problem at powerplants but often is a problem at remote natural sites. Also, time of access may be limited if, for example, the observer works elsewhere and, in addition, reliability and accuracy may be a problem. In a flood forecasting system, telephone lines may be down due to the weather or the observer may be busy elsewhere just when the data is needed the most - during a flood event. For these reasons it is doubtful that many future systems will be based on observers except, perhaps, where regular employed staff are available. However, it may be a means of obtaining data when funds are not available for other systems and it will always be important as a back-up system.

Telemarks were the first real-time system to eliminate the need for a person on-site. The original telemarks, and the vast majority of the units currently in use, are the product of older technology, being electro-mechanical rather than electronic. A major weakness is that their signal is audible tones intended for human interpretation rather than digital tones more readily deciphered by computer equipment. Newer units are electronic and use digital signals. However, all telemarks are limited in that they have no on-site memory but only sample at the time of call. They are also subject to failure of the telephone system. Nevertheless, the older telemarks will be with us for some time yet simply because there are many in use and the cost would be prohibitive to replace them all. Consequently, steps have been taken to minimize their weaknesses. Electronic devices have been built to receive and convert their audible tones to computer compatible digital tones. Auto dialers can be used to access telemarks as frequently as necessary to cover their lack of on-site memory. It is thus possible to use existing telemarks in a totally automated system. However, the system will not rival one based on DCP or DATS units - the percentage of successful interrogations is lower or less reliable due to inherent weaknesses in the audio-digital conversion. As to the newer electronic units, they may be feasible alternatives to DCP or DATS units in certain situations, such as in a flood warning system which is used only for short periods each year and where the response time is such that frequent updates are required, in which case on-site memory is of little advantage. Costs are lower than for units with memory.

DCP and DATS units represent the results of modern electronics technology. As with most things in electronics, the products are continually being improved while at the same time prices are often falling. Most new real-time systems will likely be based on these components. With on-site memory, less time and effort is spent by the data user in obtaining data and there is less risk of data loss. Also, more than one sensor may be connected to many models, permitting the user to measure several parameters at once. Although there is a tendency to treat the two units as separate emtities, the only essential difference between them is the mode of transmission, via satellite or by land-line

(telephone). In fact, the units of some manufacturers are capable of either mode. The distinction between units will probably fade in the future - most of the preferences currently expressed or the reliability problems cited relate more to a particular manufacturer or model than to the mode of transmission.

As to the mode of transmission, obviously a DCP will be used where no telephone service is available. Where telephone service is available either may be used and their relative merits should be assessed. DCP's tend to be self-contained on site, requiring neither telephone or power lines. This is a consideration in a fast response, flood forecasting situation where such lines may be downed during the flood event by severe weather. On the other hand, most users do not have their own down-links from which to obtain satellite-transmitted data and so are dependent on a third-party for their data. As more and more users of this service come into existence, it is becoming more difficult to gain access to the down-link computers. This is especially true during times of flood. System failures, power failures or even labour disputes (as nearly occurred with the ARGOS system) could render needed data unavailable. With DATS units, the user has to access each unit individually rather than go through a central service. This is less convenient and more time-consuming but the user does retain more control over the process and is less vulnerable to losing all his data.

In reality, most users will be dependent on more than one type of real-time network. This will make the data collection process somewhat more complex but may have the benefit of resulting in a more reliable system. All systems discussed above are subject to their own particular type of failure - through system diversity the user can expect to get some data even when part of his system fails. In defining the system it is essential that the data collectors and data user work closely together. Especially for flood forecasting purposes the reliability of the system under conditions of severe storm weather, fast flows and high levels, and communications systems overloads will be of prime concern. Various steps can be taken by WSC to render both the measuring system and the transmitting system as immune to failure as possible. In turn, the forecaster will need to derive alternate, back-up analysis procedures for use when not all of the system is reporting. Both will need to consider a back-up reporting system.

Even when the forecaster receives his data, one further step should be taken. Inventoried data has gone through a number of checks and verification by WSC. This is not the case with real-time data - the user must perform this role himself. For example, the bubbler line for a gauge may be dislodged. A level may still be transmitted but it will be meaningless. Stage-discharge curves may become invalid due to backwater effects or a shifting control. Any automated data collection system should have built-in checks to identify suspicious data. In addition, a knowledgeable person should screen all data and remain in contact with the data collection agency to follow-up any problems or concerns.

3. Sources of Error in Data

All measurements are simply samples taken from a population. Their accuracy is limited not only by our ability to measure but also by the extent to which the sample may or may not be representative of the population. People who work in flow forecasting should be aware of the limitations of the data that they are using in their forecast models. Additionally, those who prepare models should be aware of the same limitations as it relates to the data base that they have used in calibrating their models. Some factors (but not all) which should be considered are outlined in the following subsections.

3 1 Water Levels (Stage)

Prior to 1960 in Canada, most gauging stations did not have recording equipment. The stage observations were normally collected once a day by a gauge reader. During spring periods, these gauge observations were taken more frequently. The average of these manual readings or just a single reading has been accepted as the daily mean gauge height and is so used in determining the daily mean discharge. For certain river systems, depending upon their size and for particular times of the year, this fact has to be recognized by modelers. Often "diurnal" fluctuations during the snow melt period or even peaking at hydro-electric plants is not properly reflected in these early records. Also streams that respond quickly to large rain events may not have published values that are correct. Where it is essential to use manual records from the early periods to calibrate a model, it may prove very worthwhile to spend time comparing both the early hydrologic and climatic records for that system with the data obtained in more recent years using recorders. By doing this, an appreciation of the amount of error or possibly the amount of correction that should be made to the early period can be gained. In most regions of Canada, the Water Resources Branch (WRB) staff have carried out data review exercises. For stations where this has occurred, a statement will appear in the data publications saying "data reviewed to 1960 or to 1970". This means that the obvious errors for the period of record have been eliminated. It has also provided WRB staff with the opportunity of completing missing periods by various estimating techniques. Prior to using estimated records in calibrating models, it may be advisable to contact the appropriate District Office to examine how those estimates were determined.

There are a number of problems associated with the measurement of levels in lakes and reservoirs. Generally the measurements themselves will be a quite accurate assessment of the level at a specific place and time but this level may not be at all representative of the level the data user really wanted - the mean level of the water body. The larger the water body, the greater will be the effect of wind and barometric pressure on the water surface. Wind generated waves may produce significant "noise" in level measurements and a continuous wind for a period from hours to days may produce a significant "setup"; that is, the

drawdown of water at the windward end of the water body and the piling up of water at the other end. Once the wind dies down there may be a seiching effect of several cycles as equilibrium is re-established. On small water bodies there is often only one level gauge but on larger water bodies where these effects are more significant there are often several gauges. It is seldom that all gauges will read the same level. An attempt must then be made to define and use a procedure to produce a "mean" lake level given the various separate readings. However, it must be recalled that differences in readings may not be due to the above effects. The difference may be a valid one that should be properly accounted for - for example, there may be a slope to the water surface due to the flow through the reservoir. Also, there may be errors in the gauges themselves. Errors in datum between gauges may usually be detected from records taken during the ice cover period when wind is not a significant factor. However, errors occurring during the open water period are difficult to detect. Such errors may occur due simply to "drift" in the electronic components of a real-time system.

The effect of error in determining the mean level of a large water body is often greatly compounded by the use which forecasters must make of this data. If is often necessary to compute the net inflow by reverse routing. Given a volume-elevation curve, the change in storage over a time period is determined from the recorded levels and is added to the outflow to obtain the net inflow. This computation is very sensitive to error in elevation because any error in the change of elevation, when multiplied by the lake surface area to obtain volume, results in a large error in storage change. As an example, consider Lake of the Woods, which has a surface area of 3800 km^2. Just prior to freshet this year a single gauge error of 8 cm occurred. After combining all gauge readings and applying the usual smoothing procedures, the resulting error in change of level over 1 week was only 2 cm. Nevertheless, with this level error, the net inflow was determined to be 301 m^3/s (72 percentile) while, with the error connected, the inflow was 412 m^2/s (92 percentile). Such a difference could obviously have a large effect on how a regulating agency might react and would also significantly affect the results of a forecasting model if this data was used as a predictor variable. In this case the error was due to an adjustment of the datum on the gauge's real-time equipment, which is subject to drift. This points out the need for data users to be aware of and advised of routine gauge network maintenance and for data collection agencies to be aware of the impact of their work on real-time data users. In a network for inventory purposes only, such adjustments would be transparent to the ultimate users. However, it must also be noted that on a lake of this size an error of this magnitude, or greater, is likely to be made at any time, simply because the daily fluctuation in level at any particular site is often greater than this.

Other errors may occur in real-time data which would normally not exist in final inventory data. For example, in obtaining lake levels, the type of real-time equipment may be significant. If a

telemark or observer is used with only one spot reading per day, this reading may be significantly different from the mean for the day. For a not untypical day in July on Lake of the Woods, hourly readings varied from 323.028 m to 323.118 m, with a mean of 323.092 m - a single reading could be quite misleading. In the case of stream levels, the siting of the gauge may be a factor. During flood on swiftly-flowing streams, it has been found that the water level in a stilling well may be drawn-down due to the manner in which the water flows past the intake pipes. While the error would occur in real-time, such problems are usually known to the data collection agency and are compensated for in final records.

3.2 Flows

While levels are measured directly, flows are normally determined indirectly by means of a rating. At natural flow sites discharges are determined from level measurements by means of a stage-discharge rating curve. At man-made controls such as dams and powerhouses ratings are used both for individual sluices and for the turbines. Sources of error are considered separately below for these two situations.

3.2.1 Natural Flow Sites

When a stage-discharge curve is used to determine flow from measured stage at a natural flow site, it is assumed that there is a unique relationship between level and flow. In theory a unique relationship can only occur in a channel reach where uniform flow ($S_f = S_o$) occurs or at a control where the flow passes through the critical Froude number ($F_r = 1$). In practice uniform flow virtually never occurs in a natural channel. Consequently a great deal of effort is made to locate controls which are effective through a wide flow range (not drowned out) and to place level gauges adjacent to them. However, this may not always be possible. If no effective control exists where flow data is required, then discharge will not be simply a function of stage alone but also a function of the slope of the water surface and the rate of change of velocity over distance and time. The result will be a loop shaped rating curve where, for a given depth, the discharge will be greater on the rising stage than on the falling stage. For steep rivers ($S_f \geq 0.002$) the width of the loop is not great and the assumption of uniform flow (unique rating curve) does not introduce a large error. However, for rivers with flat gradients, such as the Red River at Emerson, Manitoba, the error introduced could be significant. More accurate flows could be determined by recording levels at two nearby sites, which would permit the inclusion of the surface slope term in the discharge computation. Alternately more frequent flow meterings are required to verify any rating, especially in times of rapidly varying flow. At any site where the effectiveness of the control and thus the accuracy of the rating is of concern, Water Survey of Canada personnel can provide information on the rating in use and on the degree of scatter of the metered flow points.

Assuming that an effective control exists and thus also a unique stage-discharge relationship, the actual rating curve is generated by metering the flow over the complete range of stage that is experienced at the site. Measurements are repeated periodically by the WSC to verify the derived curve. Ideally, the control remains constant, or stable, with time. This is true for the majority of hydrometric stations located on the Canadian shield and in the bedrock country of the Pacific region. However, at a number of sites the control is unstable; that is, its physical nature changes with time and consequently the rating curve also changes with time. This is particularly true of rivers and streams in alluvial areas such as the Prairies. Here a continual process of erosion and deposition occurs which causes the rating to shift. The change may be gradual or abrupt due to a sudden intervention such as a large flood. The shift is not constant because erosion occurs typically at certain times of the year and deposition at other times. This results in the stage-discharge relationship changing as the velocity varies for different river stages. Consequently it is possible to have a rating for lower velocity situations and a completely different one for higher velocity periods, with a transition period in between.

Whether or not the control itself is physically stable, ratings may be affected seasonally due to the Canadian climate. This, of course, is due to ice affects. During the winter the growth of ice covers and the development of restrictive hanging dams may gradually drown out a control. With sudden changes in temperature a shift in rating can be quite abrupt and, where frazil or anchor ice production is a problem, shifts may even occur diurnally. During the spring breakup ice jams may similarly affect the ratings. Where a rating is affected by ice, it is infeasible to conduct sufficient meterings to define the changing relationship throughout the ice period. Flow records are estimated, after the fact, on the basis of those meterings which are available, records at nearby ice-free stations, and past experience. Such estimates are identified in WSC publications by a "b" after the flow value. However, this is of little help in the real-time mode; it may well be impossible to effectively use data from such a station during the winter months.

Finally, even during open water in bedrock country where controls are normally stable, changes may occur gradually or abruptly due to interventions such as a very large flood event, the damming of the river by debris, beaver activity or changes caused by man such as dredging or filling-in of channels or even alterations due to other activities such as bridge construction. Consequently flow metering to verify ratings is a continuous process. More frequent meterings are required at those sites which are known to be unstable. It takes highly-trained technicians to recognize the causes of the deviations from rating curves, when to commence applying shift corrections and/or at what period these shifts should be applied. Consequently a streamflow forecaster, under the pressure of making his next forecast, needs to have an appreciation for not only what the stage and the discharge are at the

time he's preparing his forecast but he needs also to be aware of factors that could impact upon that stage and discharge. This is why it's so important that there be a good rapport established between the forecasting center and the data gathering center. Forecasters are aware that they can obtain the latest rating curves for the various sites in which they are interested from their nearest Regional Office of the Water Survey of Canada. However, they have to use caution in using either a stage figure or a discharge value on its own. They need to get assurance from the regional data control section that the stage-discharge relationship is still valid and not subject to shifting for any reason.

Apart from the problems in locating an effective control and accounting for instability, there are difficulties associated with developing a rating curve over the full range required. Meterings in the normal flow range can be readily obtained but obviously there is less opportunity to get measurements near the extremes of high and low flows. Until recently extreme events, especially high flows, had often passed by the time WSC became aware of them and was able to field a metering crew. Now, with more and more sites being real-time equipped, this is less of a problem as WSC is able to monitor the situation more effectively. However, for very large flood events, it is still not always possible to obtain a direct measurement. This could be due to lack of access to the site, loss of the measuring equipment in high flows, inability to meter due to floating debris or the measurement structure (such as a cableway) being unsafe, or the fact that the extent of flooding is so great that field staff haven't been able to measure at all the stations experiencing flooding. After the event, if it is found that the previous rating curves do not include measurements in this flow range, then special surveys are conducted to quantify the amount of flow by indirect means. While such computations are usually confirmed by subsequent meterings, it is obvious that the accuracy of rating curves extended by such means is less certain. In addition, people who are developing models and are making use of the extreme event data derived during periods of flood flows have to remember that it is only in the last forty years or so that there has been adequate equipment for measuring rivers under flood conditions. This is also a very important consideration for anyone conducting flood frequency studies. Should any particular annual extreme be of concern, the original data held by the Water Survey of Canada should be re-examined.

Anyone responsible for preparing flood forecasts should strive to make the time during a flood event to get out into the field to visit some of the key stations for which forecasts are prepared. The channel should be examined to verify that all of the water actually goes through the measuring section. Sometimes there are channels which permit flows to by-pass the measuring section. If it is found, in examining the records, that for similar stages there are quite different discharges, then checks should be made to ensure that any by-pass flows were considered. It is also possible that such channels may have been created or may have been filled-in in the intervening period between these high

flood events. It is not possible to include all of this type of information in the WSC data publications. However, once again users are advised that they are welcome to contact the various District Offices to see the original records. The Water Resources Branch is currently in the process of installing mini-computers at headquarters and in the Regional Offices. It is planned that all the historic discharge measurement data will be put into computer-usable form. Several districts are anticipating having this work completed by the end of next year. After that time, it will be possible for people to look at every discharge measurement made for a particular station. This data will be available in several forms such as a print-out of measurement date, discharge, mean width, mean velocity and stage but also as a graphical comparison of the river channel cross-section. This way it will be possible to determine areas of erosion and deposition. It will also aid in finding measurements where over/under-sounding has occured. It is anticipated that this will provide a basis for making rational adjustments to historic measurement data.

3.2.2 Man-Made Controls

Water Survey of Canada has a regular well-established program in place to continually verify and update the rating curves at natural flow sites. However, this is not the case at dams and powerhouses. Most of the data at such sites is "contributed data" and in the past has often just been accepted for publication without being subjected to data review standards. At many sites no-one has assumed responsibility for data quality and the ratings in use are very old and may never have been field-verified.

The lack of quality control at these sites is indeed unfortunate. In the overall perspective, the problem is not large as such sites apparently form only a small percentage of the total number of flow sites reported by WSC in Canada. However, such sites can only be expected to increase in number in the future and also tend to be sites with larger flow volumes of established economic value. Also, although data quality has not been a major issue at such sites in the past, demands on the quality of such data will increase in the future as more of these sites are considered for re-development and as water management agencies move to more sophisticated forecasting and modelling techniques.

Consequently the Water Resources Branch has recently taken steps to at least begin to address this problem. In the future contributed data will not be published unless it meets certain standards. Also, the Director has requested input form the Regional Chiefs on steps to improve the situation. However, the problem may be mainly one of lack of resources. The costs and manpower involved in trying to do meterings to rate all possible combinations of powerhouse and spillway flows at any single site would be excessive and unacceptable. The alternative of theoretically-derived ratings confirmed by limited field programs would also require significant resources and expertise. In addition, there are

a number of factors beyond the control of WSC which could affect the ratings, such as leakage and not adhering to specified procedures (opening sluices in prescribed sequence, etc.).

Obviously this problem is not going to be solved quickly. In the interim it is important that data users become more aware of typical sources of error in the flow data reported for dams and powerhouses. They should consider how severe the error may be at sites used in their analysis and how this error may impact on their operations. As an indicator of how severe the error may be, the ratings for the Norman Dam at the outlet of Lake of the Woods may be a useful example. At this site a re-rating program concluded that the original ratings were in error by as much as 25 percent.

As to typical sources of error, a few examples follow. All ratings are dependent on measurements of water elevation or head. Are the measurement sites properly located or are the measurements affected by factors such as losses in the approach channel, drawdown to adjacent sluices or turbines, accumulation of material on trash racks, etc.? Are readings taken often enough at powerplants to properly reflect changing conditions such as peaking operations? As to the ratings themselves, are they theoretical only or were they verified on-site? Are level measurements taken at the same location as they were for the rating? Have any changes taken place since the last rating, such as re-built piers adjacent to the sluices or revised runners in the turbines? Does the rating account for differing approach and drawdown conditions with different sluices/turbines operating? If sluice opening sequences are specified, are they followed? Are the power meters or wicket gate indicators used in turbine ratings accurate? With stop-log structures, are the logs the same size as assumed in the rating or is the actual elevation of the top log checked? Is leakage accounted for, and, if so, by what means of measurement or estimation? Is the means appropriate to the degree of leakage and has it been verified? Does leakage also occur through idle turbines?

Clearly there are many potential sources of error. These should be discussed with persons familiar with the site and steps taken to quantify unknowns wherever possible. Especially with older installations, alternate means of monitoring the flow either upstream or downstream should be considered if possible.

4. Data Collector - User Needs

Based on the discussions of the previous two sections, a number of conclusions can be drawn regarding the needs of data collectors and users operating in the real-time mode. Most fundamentally, the user needs to receive his data in a timely fashion and with an acceptable standard of reliability. The data needs to be consistent over time and a statement regarding its accuracy would be most useful in assessing the impact of errors in data upon resultant forecasts.

Beyond this, it is clear that the performance of each group could benefit greatly from discussion or good communications. The user needs to have a fundamental awareness of the limitations of the data he uses, its sources of error, the relative benefits of different data collection systems and how the operations of the data collector in maintaining the network may impact on his data. The collector needs to be aware of the requirements of the user, the impact of his activities on the user, how the data is to be used and the importance of accuracy.

It is also clear that study or research is needed in several areas. Many flow sites cannot be used in the real-time mode during the winter months because their ratings are affected by ice conditions. Procedures are needed to correct readings for this effect. Similarly, procedures are needed to correct ratings affected by weed growth during the summer. Net inflow computations to lakes are unduly sensitive to errors in the mean lake level. Better methods of using the data from one or more stations to compute the mean, or procedures to better gauge the water body, would help to alleviate this problem. Also, no standardized procedure exists to develop or verify ratings at man-made controls. Such a procedure needs to be developed which could provide ratings at a reasonable cost. Alternately, new measurement techniques are needed to economically measure total flow upstream or downstream of such structures. Improved flow measurement techniques are also needed for rivers with flat gradients where the rating curve is not single-valued but loop-shaped. Increased demands for accuracy in support of forecasting have rendered some approximations currently in use inadequate and, further, as more gauge sites are required on the prairies, more can be expected to have this problem.

From the way the gauge network across Canada has developed, it can also be inferred that there is a need for network planning. Most gauges were originally sited in order to inventory Canada's water resources. Additional gauges were subsequently added to fulfill specific local needs. As real-time equipment became available, it too was added, usually to existing gauges, to fill the perceived needs of the sponsoring agency. Benefits could accrue from a more global overview of network needs.

Finally, one further observation can be made. In terms of real-time data acquisition, we are in a transitional state. Many of the problems confronting us today will have faded away 5 years from now. For example, the chronic problem of the past was not being able to get enough real-time data. This is quickly changing. The current major problem is one of being swamped with data and trying to develop automated accessing, verification, storage and reporting systems to cope with the volume. This problem will also pass with time but will probably be replaced by new, equally challenging problems.

5. Data Collector - User Interaction

Hopefully it is clear by now that the need for communication between agencies collecting data and agencies using data has been stressed throughout this paper. Further, the level of communication being called for is not just a superficial one of dealing with raw data, but also a deeper one with the objective of fostering better understanding between the groups. To further develop this view, consider the following three thoughts.

First, we all tend to focus most on that which is most familiar to us. This leads to communication breakdowns. For example, the data collector will typically be fully aware of the multitude of error sources listed previously. Since he is usually not conversant to the same degree with the techniques of forecasters, the problems to be encountered seem fewer and simpler. After all, it is simply a matter of inputting the data to the proper equation, is it not? However, the data user is aware of a multitude of problems in his own area. For example, to the designer who has just used two different frequency distributions and has come up with two markedly different design floods, the problems involved in metering flows seem superfluous. After all, it is a simple enough procedure, is it not? In fact, the performance of each might be improved through a better understanding of the needs or problems of the other. However, it takes time and effort to learn and appreciate the perspective of another.

Second, consider a common statement by data collectors that forecasters tend to demand more data than they really need and tend to demand it more frequently and urgently than needed. This may in fact be the case; however, it is just as likely an indicator of insufficient communication. Forecasts are always, and will always be, in some way inadequate simply because we are not dealing with a totally deterministic system. The question of inadequacy is always there, it is only the degree which varies. Consequently the forecaster must always live with the concern that his work is not good enough. In such an environment a good forecaster is similar to a detective - he isn't sure what he is looking for or how to use it but it may be useful and he wants to leave no potential clue unconsidered. The forecaster should be able to explain this need to the collector agency and give some examples of where extra information did improve his forecast. After all, requests for additional resources must be justified. Also, he should learn from his experience and advise the collector agency so that unfruitful procedures may be dropped. If the forecaster can properly explain his need, then the collector agency won't feel he has asked for too much and will try to comply - if he can't justify his need then he probably has asked for too much.

Third, the time is ripe for enhanced co-operation between data collectors and users. In the past the roles of the two tended to be distinct and separate. However, with the advent of real time data

collection on a large scale and the simultaneous growth of forecasting agencies, the operations of the two groups are being drawn closer together. The next 5-10 years will probably see a greater change in the role of, and the methods used by, the data collection agency than has been seen in the last 50 years. As part of this process, new policies and procedures will be defined. Through discussion and co-ordination there is a great opportunity for forecasters to influence the process and for collectors to further enhance the utility of their service. On the other hand, both groups are being increasingly challenged by ever more rapidly changing technology and the increasing awareness and demands of the public. With continued limited resources, neither group can afford the inefficiency and the duplication of effort that lack of full co-operation could bring.

To foster deeper understanding between data collectors and users, and to address the needs and problems of each, the authors feel that cooperative interaction must be established between the groups. The first step in establishing cooperative interaction could be considered as what is occurring at this and similar workshops and conferences. A medium is established where the activities and problems of the two groups can be presented and discussed. Further, and maybe more important, new concepts and approaches are acquired and long lasting contacts with those in both the data gathering and forecasting fields are made.

The second step in establishing cooperative interaction could be the formation of discussion groups in each region across Canada. These groups could be centered around each regional WRB office and would consist of WRB personnel plus those data users involved in forecasting that most often are in contact with them. By centering these discussion groups in each region, costs associated with meetings would be minimized and the problems or procedures peculiar to each region would be addressed. Further, discussion would take place between those who actually must interact with each other.

A third step could be a follow-up workshop of the same nature as this one. This would pull together the results obtained in each region.

Computational Procedures

Technical Workshop on Streamflow Forecasting

Theme Paper for Working Group 3

by

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Computational Procedures

Technical Workshop on Streamflow Forecasting
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Streamflow forecasting is carried out for a variety of purposes and covers a great range of time scales. An earlier paper (1972) by the writer reviewed various forecasting procedures and much of the work quoted is still relevant. Traditionally, the primary purpose of forecasting procedures is often considered to be flood forecasting, but from an economic viewpoint, continuous streamflow forecasting for the operation of water resources projects is becoming more important due to the complexity of competing water use demands. Depending on the nature of the watershed or the water resource system forecasts may range from short term flood forecasts to longer term seasonal volume forecasts.

The value of any forecast is dependent on how far ahead an accurate forecast can be made. This will be referred to as the lead time of the forecast. The lead time of the forecast is influenced by the watershed characteristics and the nature of the runoff producing mechanism such as intense rainfall or the more moderate snowmelt processes and is a critical factor when considering the feasibility of making flood forecasts both adequate and useful. Both the lead time and the value of the forecast are modified and influenced by the presence of lake or reservoir storages and by delay through the channel system.

Seasonal volume forecasts are made for snowmelt fed rivers, where winter snowpack accumulations can be measured and used to give statistical estimates of volume runoff. These volume forecasts are widely used to determine the operation of systems with reservoir storage adequate for seasonal regulation. An example is the Columbia River system which is jointly operated by the United States and Canada under the provisions of the Columbia River Treaty, B.C. Hydro & Power Authority (1980). Depending on the forecast, the system may be operated primarily for maximisation of

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power benefits, or, when a large volume is forecast, primarily to reduce downstream flood risk. The optimum operation of such a complex system depends not only on the seasonal volume of runoff, but also on the time distribution of the runoff volume. From recorded streamflow data, it is possible to define an average, or most likely, distribution of runoff, and it is also possible to define early peak and late peak flow patterns of behaviour. In addition to this statistical approach, a watershed model can be used to update the estimates of flow distribution. These updated estimates become more and more accurate as the season progresses, so that the system operation can be revised and greater flood control power or benefits can be achieved. This watershed modelling approach, in combination with many years of observed meteorological data, can be used to estimate probability values for the possible patterns of future runoff. These patterns, in conjunction with an economic objective function, can be used to determine optimum operation for the next time period.

Rainfall Floods

For small, fast responding watersheds, it is doubtful whether real time flood forecasting is viable. With so little warning, even evacuation of people may not be possible. For such watersheds, it is essential to make adequate design flood studies and ensure that people and property are adequately protected from the hazard. Watershed modelling is the best method for carrying out these design studies, because it coordinates and incorporates the total data base and estimates the peak flow, the volume and the time distribution of runoff.

Forecasting runoff from rainfall depends very much on the definition of areal distribution and time distribution of the rain storm. Such storms can range from intense local thunderstorms, covering just a few square kilometers up to some two or three hundred square kilometers and lasting a few hours or less, up to synoptic scale cyclonic systems of several thousands of square kilometers and lasting some two to three days. A valuable study of these storms is presented in the WMO publication on probable maximum precipitation (1973) which is based on analysis of storms in the Pacific Northwest and is derived from an earlier report by the U.S. Weather Bureau (1966). The thunderstorm category is very limited in extent and produces floods on the small, fast responding watersheds discussed in

the previous paragraph. The synoptic storms can influence quite large watersheds and can build significant flood peaks which take time to move through the river systems. Flood warning for these events can be given in reasonable time, especially if reservoir storage is available to modify the flood. If this reservoir storage is to be used to best advantage then it is important to make a good forecast of both flood volume and flood hydrograph shape. If too much storage is committed too soon, the net effect may be to accelerate the flood peak through the full reservoir, so that damage is actually increased by the attempted flood regulation. Rainfall streamflow forecasts for these synoptic scale events require extensive data networks to define the areal variability of precipitation, and these complex input values need to be processed by a reasonably flexible watershed model. One approach to handling this variability is to sub-divide into a number of small sub-basins and then to combine the flows using a stream routing model, Rockwood & Kuehl (1968), Quick & Pipes (1976). This relatively short term rainfall runoff computation is usually carried out on an event basis, but it is necessry to initialise the soil moisture and groundwater status of the system, so that some longer term accounting procedures are required. For example, the initialisation can be based on an antecedent precipitation index and the preceeding streamflow, which is a measure of the groundwater status.

Snowmelt Forecasts

In contrast to rainfall forecasting, snowmelt is a much more predictable situation and is usually of concern for medium and larger watersheds. Snowmelt usually continues for a period of several weeks or even months. The snowpack is essentially a large reservoir storage which can be measured at the start of the season and can be monitored continuously by snowpillows during the accumulation and depletion periods.

Estimates of snow cover from satellite data is already being used by some forecasters and this approach is likely to show marked improvements with the use of radar imaging. Various papers are appearing on this topic, for example, Peck, Carroll & Van Demark (1979) and Rango & Peterson (1980).

A clear distinction should be made between prairie snowmelt runoff and mountain snowmelt behaviour. Prairie snowmelt involves small snowpacks of

highly variable distribution. The melt season is relatively short and the antecedent soil conditions have a large influence on the volume of runoff, Goodison & McKay (1978). Sampling the snowpack is a problem because of wind redistribution which concentrates snow in drifts and gulleys. By comparison, mountain snowmelt is more predictable. Mountain snowpacks are usually larger and more extensive so that the snowmelt season is more prolonged and vigorous. The mountains themselves impose an orographic discipline on the meteorological processes, so that there are distinct and definable gradients of precipitation and temperature, giving a more uniform behaviour within each elevation zone. Because the volumes of runoff are greater and more continuous, the antecedent moisture conditions play a smaller role in the runoff process and calculation of streamflow is less sensitive to antecedent errors.

Forecasting models fall into two major categories, firstly the statistical seasonal volume models and secondly, the watershed models which are used to predict the pattern of runoff in the medium to short term, estimating both flows and volumes. There is a great difference in the complexity of these two model types and the watershed models require much more continuous and detailed meteorological inputs and high quality reference streamflow data. The seasonal volume forecast models are restricted to snowmelt forecasting. The snowpack is sampled in the spring and, together with measures of antecedent runoff conditions, these values are used as input to regression forecast equations. As with all statistical methods, the strongest and best defined statistical parameter is the mean, and regression forecasts show a strong dependence on this average runoff volume value. The variation about the mean is less well defined so that the forecast can only be given within certain confidence limits. This uncertainty is not only a statistical problem, because forecast errors are also influenced by future weather patterns and by errors in the estimation of snowpack and antecedent conditions.

Forecast Model Design

Watershed models vary in design according to their application. Rain runoff event models are usually relatively simple because they are only concerned with the fast runoff response. The main problem with an event model is to obtain fast and accurate estimates of the areal distribution

and intensity of rain. The second problem is to assess the antecedent moisture conditions, so that effective rainfall for fast runoff is correctly estimated. The WMO Intercomparison of Rainfall Runoff Models was reported in great detail in 1975, 1976 & 1977 following the Bratislava meeting. Many more papers have appeared since, but the basic problem areas mentioned above are still the primary difficulties.

Watershed models designed for calculating combined snowmelt and rain runoff are usually more complex because they are forced to deal with longer term runoff in which the medium and slower components of runoff are significant. Somewhat paradoxically, the most important aspect of a snowmelt watershed model is the representation of the meteorological processes. This meteorological sub-model must grapple with the problem of distributing point measurements of precipitation and temperature across the total area and elevation range of the watershed. The temperature lapse rate distribution is particularly important when calculating snowmelt rates, which are then combined with rainfall to give a total input of water to the watershed system. There is also the question of whether precipitation falls as rain or snow, which is quite sensitive to the temperature lapse rate. This meteorological data distribution is clearly very much related to the question of data network density. In theory, a much denser data network can be substituted for the modelling assumptions, so that the more data we have, the less we need to know about the physics of the meteorological processes. At the present time, funding for data collection is quite limited, so that there is considerable scope for hydrological ingenuity in making the most of a limited data base.

Some combined snowmelt and rainfall runoff watershed models are designed to operate on a continuous year round basis and will be documented in the report on the WMO Snowmelt Intercomparison Study, Stockholm, Sept. 1983. Some earlier descriptions of some models were given at the WMO Bratislava Symposium (1975) and were published in the Hydrological Sciences Bulletin in March 1977. Snowpacks are computed by the model, usually for each elevation zone, and these calculations keep track of the snow accumulation and depletion, so the model operation depends only on having a continuous meteorological data input. Such an automatic operation, with no intervention, has been used to estimate flow records for past periods when meteorological data was available, but no streamflow records existed. For

real time forecasting, updating the model with the latest streamflow information and snowcourse information appears to be an attractive idea, but it is not simple and research is currently underway to develop good updating methods which do not disturb the underlying stability of the existing models.

A workshop proceeding edited by O'Connell (1980) reports on an attempt to use Kalman filtering to update forecasts, but no significant improvement was found on either a 24 hour update or even a 1 hour update and they state that, "the errors occurring on the rising links are peaks ... are found to be very similar in magnitude and sign for all models tested, ...". This study assumed the flow data to be 100% accurate and a random error in the model. In contrast, our own attempts at updating have indicated that the major errors are in the precipitation inputs, which can be evaluated in hind sight, but is very difficult to detect in real time.

Data Reliability

To be reliable, data must be accurate, continuous and with a network density adequate to define areal variability.

Data accuracy is highly dependent on the type of measurement. For example, temperature data are relatively simple to measure and temperature data are robust and reliable. In contrast, radiation measurements are complex and difficult, and can be quite misleading. The radiation processes involve a complex accounting of the net effect of short and long wave radiation, which requires information on such highly variable parameters as albedo, cloud cover, humidity, air and surface temperatures, forest cover and aspect. At the recent WMO Snowmelt Modelling Intercomparison Meeting in Stockholm (September 1983) it was reported that the majority of snowmelt modellers were relying on temperature measurements and were using them as indices of energy exchange to the snowpack.

Streamflow forecasting of any type depends on the accuracy of streamflow gauging and yet streamflow is one of the more difficult measurements. A stable channel cross-section with good flow characteristics is required. Accurate velocity and depth measurements need to be integrated to estimate discharge, and these measurements have to be made while the river flow itself is varying with time. From such measurements, an average stage-discharge relationship is constructed, but

the majority of the data points lie in the medium to low flow range. Flood discharges are usually extrapolated interpretations of this stage-discharge relationship and can be subjected to considerable errors. Professor Sugawara (1983) considers that high discharges contain so much error that he uses the logarithm of the discharge when fitting his model. The effect of using the logarithm is to de-emphasize the peak flow and to weight the calibration towards the low and medium flow range.

Large rivers have a more gradual response, so that there is time to make a measurement near the peak flow condition, and this is especially true for snowmelt rivers. In contrast, small rivers, subject to rain floods, have a very flashy behaviour and floods are often past before a measurement can be made. Dilution gauging is being used in some difficult steep mountain stream situations.

Having made these comments on the possible inaccuracy of streamflow measurement, it is worth emphasizing that the measured streamflow is used for calibrating all forecasting models, just as if the flow data were 100% accurate. It is difficult to suggest any alternative, but there must be both systematic and non-systematic errors present in the streamflow data. It is only when such errors become very large that they can be finally recognised. For example, there was one situation where the forecasts had been reasonable, but, as the flows increased, forecast flows were, later, found to be some 30 to 40% lower than the so-called recorded flows. It was then discovered that the particular river gauging station was suffering from backwater effects generated by a new impoundment downstream, and these increased backwater stage values apparently indicated very high flows. Unfortunately for the forecaster, it is not always possible to blame all forecast errors on streamflow data error.

Data recording and transmission is now easy and reliable. Data sensors are still the major problem, and partial failure, rather than complete failure, can be quite misleading and troublesome. In designing a forecasting data network, this question of sensor reliability is a key issue. Robust and reliable measurements, such as temperature data, are ideal for forecasting purposes. Many other measurements are far less reliable, for example, precipitation gauges suffer from catch deficiency, electrical failure or icing, and the problems of radiation measurement, discussed earlier, are compounded by sensor problems. To compensate for

these many varieties of data loss, it is desirable to design forecasting models so that they operate on the most reliable data. Also, a certain degree of model redundancy, or model versatility is highly desirable, so that if one source of data is missing, an alternative method of computation can compensate for the missing information. Data transmission has been somewhat lightly passed over, but a mention might be made of the meteorburst system for gathering data. This Canadian invention, whereby data transmissions are bounced off micrometeorites, appears to offer reliability and economy, even in the far North, and is well tested in the American Snotel network.

Watershed Model Improvements

Watershed models are made up of various sub-models which describe different aspects of hydrological behaviour. Typically these sub-models are:

I. Meteorological Sub-Model:	Distribution of meteorological data such as temperature and precipitation by elevation and area. [Temperature lapse rates, precipitation gradients. Accumulation and depletion of snowpacks.]
II. Snowmelt Model:	Estimation of snowmelt by elevation zone. [At present by temperature index approach. Also rain on snow.]
III. Soil Moisture Model:	Subdivision of rain and snowmelt into fast, medium and slower components of runoff. Estimation of evapo-transpiration losses, including interception.
IV. Routing Model:	Time distribution of runoff components from watershed to outflow point. Additional options for lake and reservoir storage within watershed.
V. Numerical, Graphical & Statistical Output:	Model output and performance evaluation.

As far as possible, these sub-models should be evaluated and calibrated independently, which is possible, to some extent, in the meteorological model and the snowmelt model. The soil moisture and routing models are not directly separable and tend to interact, so that they have to be evaluated as part of the overall performance. But even this more complex soil moisture routing behaviour can be simplified by observing watershed response during long recession periods to evaluate groundwater routing, and during high intensity rain events to estimate fast runoff response.

Without doubt, the highest priority, if we are to achieve more accurate streamflow forecasting, is to develop better estimates of areal distribution of precipitation, both snowfall and rain. Dense networks for the measurement of precipitation may be considered too expensive, but costs of remotely operated stations are reducing and radar measurements of precipitation could be more widely exploited, Bonser, (1982). It may be more economically feasible to achieve some limited increase of data network density, but to combine this increase with better alogorithms for handling the elevation and areawide variability of precipitation. For example, synoptic information may indicate whether storms are likely to be widespread or to have local convective cells. Certainly, there appear to be distinct differences between summer and winter precipitation patterns. Utilising wind data may lead to better definition of upslope and downslope orographic patterns. From an instrumentation viewpoint, there is still the problem of catch efficiency, especially as we install more remote sites where wind and ice-capping are problems.

Temperature lapse rates are known to be quite variable, but estimation techniques are at present only approximations. Some systematic variations are recognisable, such as conditions during heavy rain or during clear, open sky conditions. These temperature lapse rate assumptions can have a considerable influence on the calculation of snowmelt rates and in determining the elevation at which rain turns to snow.

Headway in improving these precipitation and temperature estimates offer the greatest rewards in terms of forecasting accuracy.

All the current fully operational forecast models tested in the recent WMO Snowmelt Intercomparison estimate snowmelt by using a temperature index method. Two other experimental models are using additional radiation and wind data, but it is too early to establish whether these extra data

improve the snowmelt estimates. Various improvements on the simple degree day index approach are currently in use. One approach attempts to recognise the additional melt during clear sunshine by using the daily temperature range as an index of radiation. The importance of humidity in a warm air mass is approximated by using the minimum temperature as a surrogate dewpoint. These additional terms, Quick & Pipes 1976, can sometimes nearly double the melt rates which would be estimated from mean temperature alone. Despite all the work that has been done on snowmelt, there is still good scope for accurate experimental measurement of snowmelt and correlation with meteorological variables, especially to determine the value and application of wind and radiation data. Some other studies are reported by Colbeck & Ray (1979).

Conclusion

Streamflow forecasts fall into two main categories, streamflow seasonal volume forecasts and shorter term flow forecasts. The value of the forecast depends on how far ahead the forecast can be made, and this has been referred to as the lead time of the forecast.

Rainfall runoff on small watershed can only be forecast with very small lead time, and for such watersheds, flood warning is of little value. Good design studies are needed so that flood protection can be provided against moderately extreme events.

For larger watersheds and particularly for snowmelt runoff, forecasts can be made with reasonable lead time and can be used to operate flood control reservoirs and to achieve economic benefits both for floods or for other water resource objectives, such as hydropower production.

The largest improvement in flow forecasting depends upon achieving more accurate estimates of the areal distribution of precipitation. This applies to both rain runoff and to snowmelt. The areal distribution must be known both by elevation and across the watershed. This can be achieved partly with more data stations and partly from a better physical understanding of the precipitation distribution processes, especially due to orography, aspect and wind. Radar measurements have yet to be exploited.

For snowmelt forecasting, the spatial variation of temperature, particularly the temperature lapse rates, are partially understood, but

there is still scope for a better definition of the temperature variation. Again this can be achieved with denser data networks, or, more economically, by having a better description of the physical processes.

Forecasting procedures depend on the reliability and accuracy of the data base. Some types of data, such as temperature, are reliable and robust, whereas data, such as radiation data, is of doubtful accuracy and subject to failure. Precipitation data suffers from catch deficiency, and high areal variability. Streamflow data is used for reference as if it were 100% accurate, whereas in reality there can be significant errors. To guard against data loss, the model should be designed with some redundancy or versatility, so that a forecast can still be made, in spite of some missing data.

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MANAGEMENT & ORGANIZATION

SAINT JOHN RIVER FORECAST CENTRE

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MANAGEMENT & ORGANIZATION

SAINT JOHN RIVER FORECAST CENTRE

SYNOPSIS

This paper describes the management and organizational structure of the Saint John River Forecast Centre, located at Fredericton, N.B., which has as its mandate the development "of a flood forecasting capability for the New Brunswick portion of the Saint John River Basin". It functions under the aegis of the Flood Forecasting sub-agreement of the Federal/Provincial General Agreement Respecting Flood Damage Reduction. (Figure 1)

Because it is an intergovernmental body, its senior management is the Steering Committee, established under the Agreements, which is composed of two Provincial and two Federal senior civil servants. Technical support is provided by a similarly constituted Technical Committee and other Committees established to provide expertise, advice and guidance on ice formation break-up and jamming, flash floods and public information. The Saint John River Basin Hydrology Committee is an out-growth of the World Weather Watch Project on the Saint John River and it provides an opportunity for coordination of snow surveys, meteorologic and hydrometric network development and analysis and technical exchange since its membership comes from a variety of Federal, Provincial, State of Maine and U.S. Federal agencies.

The day to day operation of the Centre varies depending on the season and river conditions. There are basically two operational modes - one during the spring freshet period and the other during the balance of the year.

The Centre functions under a Director who is also Program Manager of the Flood Damage Reduction Program. He is committed full time during the spring and as required for the balance of the year. The regular full time staff consists of a Forecast Engineer and a Forecast Technician. They are supported year round by the N.B.D.O.E. Met Centre which is continually manned by two met technicians. In the spring, this basic group is augmented by one or two technicians from N.B.E.P.C. and, in the early part of the year before the ice leaves the rivers, by a technician from Water Survey of Canada.

The basic hydrologic and hydrometric information required for model simulation of the Saint John River is acquired by the Centre through a very extensive communication network involving telephone, telecopier, telex, data collection platforms (D.C.P.'s), computer terminals and satellites. The collection of the data is a cooperative operation including many Provincial, State, Federal and private agencies and people.

Meteorological input to the program is provided by A.E.S. in terms of historic and forecast information and 50-60 weather observers in N.B., Maine and Quebec report met parameters twice daily by telephone to the Centre or to a sub-office established for this purpose at Grand Falls. Six remote weather observation stations transmit observations by D.C.P.'s and satellite which are available to the Centre by accessing the NOAA computer in Suitland, Maryland.

The N.B.D.O.E. Met Centre monitors all A.E.S. and N.W.S. products received on circuits 180 and 181 and on the facsimile recorder (circuit 1835) and provides the River Forecast Centre with appropriate weather forecasts and historic analyses.

River level and flow data is obtained from a series of 33 hydrometric stations along the river which have telemarks to permit access by the Centre at all times. Six remote stations transmit via D.C.P. and satellite, one of which also provides weather data. Five hydroelectric stations also provide river flow, level and plant discharge data.

Snow pack information is obtained from a bi-weekly co-operative snow survey at some 60 locations throughout the basin. Nine agencies are involved in these surveys which are timed to coincide with the schedule laid down by the Eastern Snow Conference. The data is collated and analyzed by the staff of the River Forecast Centre. The areal extent of the snow cover is obtained from analysis of satellite imagery. Snow cover maps are presently received from three groups who are experimenting with three basic mapping techniques.

Forecast and historic meteorological data, hydrometric and snow pack information are fed into the Provincial Univac main frame computer using terminals at the Centre each morning during the spring freshet. The SSARR model is used to produce five day forecasts. The printout is received at the Centre and also at the N.B.E.P.C. River Control Centre (R.C.C.) at the Mactaquac Hydro Plant.

The R.C.C. use this output of forecast flows in their SOCH model to determine plant discharge patterns which are used as input to the DWOPER or ESTUAR model at the R.F.C. to produce five day water level forecasts for the river section between Fredericton and Saint John.

The number of forecasts issued each day varies from one to three depending on the river and flood situation. Five day forecasts are issued only to the Federal and Provincial Government agencies whereas three day forecasts are issued to the media, via N.B.I.S. One day forecasts with future trends are placed on a taped message available by telephone to the public. The Director also maintains direct contact with radio and T.V. stations and the newspapers when the situations warrant it.

The annual budget for the Centre is about $150,000 shared equally by the Federal and Provincial Governments. N.B.E.P.C. contributes 1/6 of the total or 1/3 of the Provincial share. N.B.D.O.E. contributes the balance. Revenues for services provided by the Centre amount to about $11,000 annually for flow forecasts and weather services.

A significant amount of assistance is provided by the various agencies involved with the forecasting program which is not covered by the budgeted amounts.

THEME PAPER WORKING GROUP 4

MANAGEMENT & ORGANIZATION

SAINT JOHN RIVER FORECAST CENTRE

INTRODUCTION

Recognizing the serious social and economic effects of floods in many areas of New Brunswick, the Provincial and Federal Governments have embarked on a number of initiatives to reduce both the damages caused by floods and the large compensation claims which have been paid in recent years. On March 31, 1976, the ten year General Agreement Respecting Flood Damage Reduction was signed. The termination date has since been extended to March 31, 1991. Subsidiary five year agreements for Flood Forecasting, Flood Risk Mapping and Studies were also signed in 1976 and 1977. The termination dates were later extended to March 31, 1986 for the Flood Risk Mapping and Studies Agreements and to March 31, 1987 for Flood Forecasting Agreement.

Prior to 1972, the Water Resources Branch (W.R.B.) of the New Brunswick Department of the Environment (N.B.D.O.E.) and the New Brunswick Electric Power Commission (N.B.E.P.C.) were involved each spring in relatively unsophisticated flood forecasting programs for the Saint John River. Towards the end of 1972, these two agencies joined in their efforts to develop a flood forecasting system for the Saint John River Basin using modern computerized techniques. A review of available forecasting models was carried out and the Streamflow Synthesis and Reservoir Regulation (SSARR) model of the U.S. Army Corps

of Engineers was selected. It was obtained in February 1973 and a Task Force consisting of representatives of N.B.D.O.E., Water Resources Branch; N.B.E.P.C. and the Inland Waters Directorate (I.W.D.) of Environment Canada, was formed to adapt the model for application to the Saint John River Basin. After minimal calibration, the model was available for operation by the end of March. It was used effectively for forecasting the major flood event later that spring from the "Saint John River Forecast Centre" which had been established on an interim basis at the N.B.E.P.C. head office building in Fredericton. Forecasts were then issued each spring between 1973 and 1977 from this Centre utilizing staff from both the W.R.B. and N.B.E.P.C.

During this period, the W.R.B. approached Environment Canada (D.O.E.) for support in the New Brunswick flood forecasting program and as a result of subsequent negotiations, the Federal Provincial Agreement Respecting Flood Forecasting was signed in August, 1977. This officially established the Centre in its present form and it was set-up in permanent quarters within the W.R.B. offices shortly thereafter.

Recognizing the international implications of a forecasting program on the Saint John River, (Figure 1). The W.R.B. promotes the adoption of the Basin as a World Weather Watch (W.W.W.) project under the World Meteorological Organization (W.M.O.). The suggestion was accepted in 1974 and gave further impetus to the development of the Centre and the flood forecasting program in New Brunswick.

PROGRAM MANAGEMENT

From its inception in the late 60's and 70's, the New Brunswick flood forecasting program has been a cooperative effort involving many federal and provincial departments and agencies and even some private organizations. This was expanded even more during the World Weather Watch Project between 1974 and 1978 when the international aspects of the Saint John River Basin were highlighted and various U.S.A. and State of Maine agencies became involved. Following the signing of the Federal/Provincial Agreements, a committee management structure was superimposed and the number of co-operating agencies was increased even further.

Overall responsibility for the Flood Damage Reduction program has been given to a Steering Committee by the General Agreement. This Committee is made up of four senior civil servants. Two Federal members are from Environment Canada and the Provincial members are from the Departments of Environment and Municipal Affairs.

Under the terms of the Flood Forecasting Agreement, a Technical Committee was set up by the Steering Committee consisting of four members. Two Federal members are from the Inland Waters Directorate and Atmospheric Environment Service of Environment Canada. The two Provincial members represent the Water Resources Branch of the Department of the Environment and the New Brunswick Electric Power Commission.

A Program Manager was also engaged to administer all of the sub-agreements. He also serves as Director of the Saint John River Forecast Centre and reports to the Steering Committee both directly and through the Technical Committee.

Two sub-committees of the Technical Committee under the chairmanship of the Director, contribute technical expertise and assistance to the program. The Sub-Committee on River Ice has as its mandate the development of methods to forecast the onset of ice break-up and ice jams and to collect and collate data on ice formation, break-up and jamming. The membership on this committee includes representatives from the following agencies:

Water Resources Branch, I.W.D., Environment Canada

Atmospheric Environment Services, Environment Canada

National Water Research Institute, Environment Canada

National Hydrology Research Institute, Environment Canada

Water Resources Branch, N.B. Dept. of the Environment

The New Brunswick Electric Power Commission

The N.B. Department of Transportation

The Saint John River Forecast Centre.

A sub-committee on flash floods has also been established to investigate various techniques of forecasting flash floods and to produce a plan for a flash flood warning system for one of the smaller tributaries of the Saint John River. Membership on this committee includes representatives from the following agencies:

Water Planning and Management Branch, I.W.D., Environment Canada

Atmospheric Environment Service, Environment Canada
Water Resources Branch, N.B. Dept. of the Environment
Saint John River Forecast Centre

A Public Information Committee has also been established to promote the Flood Damage Reduction Program in general as well as the Flood Forecasting Program. Membership includes public relations officers from the N.B. Dept. of the Environment and the regional office of Environment Canada along with personnel from Water Planning and Management, N.B. Water Resources Branch and the River Forecast Centre.

Following the completion of the World Weather Watch Project in 1978, it was considered to be imperative to continue the liaison and cooperation which had been developed between various Federal U.S. and Canadian agencies along with State and Provincial participants. This was accomplished by establishing the Saint John River Hydrology Committee with representatives from the following agencies:

Environment Canada
N.B. Dept. of the Environment
N.B. Electric Power Commission
Quebec Ministère des Richesses Naturelles
National Oceanic & Atmospheric Administration
U.S. Army Corps of Engineers
U.S. Geological Survey

This Committee meets twice a year alternating between Canada and the U.S.A. It has proved invaluable in coordinating snow surveys, hydrometric and meteorological data collection and network planning and technical information exchange.

RIVER FORECAST CENTRE-OPERATIONS

The Centre functions on a daily basis from mid-March to the end of the spring freshet - usually mid-May. During the remainder of the year, forecasts are provided for special events such as hurricanes, ice jams or other high precipitation events which might cause flooding or a rapid rise in river levels. At times when the Centre isn't producing forecasts for these purposes, a forecast is provided to the N.B.E.P.C. Energy Control Centre on about a once a week basis. The timing of these forecasts is arranged by consultation between the River Forecast Centre and the Energy Control Centre.

Because of these commitments, the Centre is functioning, and in a position to respond to potential flood events almost daily throughout the year.

During the spring freshet period (mid-March to mid-May) the Centre is fully activated including all external support services. Weather input is provided by the N.B. Dept. of the Environment Met Centre utilizing data obtained over A.E.S. circuits 180 and 181 and a facsimile recorder on circuit 1835. At this time, A.E.S. at Bedford N.S, provides special forecast messages which are obtained by the Centre via their circuits and by accessing their computer using a Silent 700 terminal. Historic weather data is obtained from 50 to 60 weather observers in New Brunswick, Maine and Quebec who transmit their readings to the Centre by telephone and in some cases via an intermediate

receiving post at Grand Falls.

Data from six weather observation stations located in remote areas are accessed by use of D.C.P.'s and satellites through the NOAA ground receive computer station at Suitland, Maryland. One of these also provides river levels along with five other D.C.P.'s which provide river levels at various remote locations along the river. Levels are also obtained at 33 other locations be means of telemarks accessed by telephone from the Centre. Additional flow data is obtained from hydroelectric stations at Mactaquac, Beechwood, Grand Falls, Tobique and Tinker on the Aroostook River.

Information on the snow pack is obtained from periodic (bi-weekly late in the season) snow surveys at some 60 locations throughout the Basin carried out by nine agencies and private companies in N.B., Maine and Quebec. The areal extent of the snow pack is provided late in the season whenever cloud free satellite imagery is available. Presently, three groups are carrying out experimental programs using three basic techniques. The output from these programs in the form of snow cover maps is provided to the Centre. The maps are transmitted by telecopier from NOAA/NESS in Suitland, Md and from A.E.S. in Toronto A local contractor who utilizes enhanced satellite imagery, which has been delivered by courier from the Toronto office of A.E.S., delivers the maps by hand. It is expected that in the future, the local contractor will provide an acceptable product to the Centre and both A.E.S. and NOAA will discontinue the service as soon as their current research into snow cover

mapping techniques and procedures has been completed.

Forecast and historic meteorological data, hydrometric and snow pack information are fed into the Provincial Univac main frame computer through terminals at the Centre each morning. A model, called SSARR (Streamflow Synthesis and Reservoir Regulation) is used to produce five day forecasts of flow at thirty-two locations along the Saint John River. Continuous back-up of the Univac is provided by the I.B.M. 3032 at the University of New Brunswick. The two main frame computers are remote from the Centre but the print-out is obtained on a 600 lines/min printer located in the same building as the Centre. A print out is also obtained simultaneously at N.B.E.P.C.'s River Control Centre located at the Mactaquac Hydroelectric Generating Station.

The River Control Centre usesthe SSARR flow forecasts in the Tennessee Valley Authority's Simulated Open Channel Hydraulics (SOCH) model to simulate open water longitudinal profiles along the Mactaquac headpond which,when related to prescribed rule curves,permits them to develop operating plans for plant discharge. These forecasts of discharge at the Mactaquac dam are then communicated to the River Forecast Centre and fed into either the water level routine of the SSARR model (called ESTUAR) or the DWOPER (Dynamic Wave Operational model) to obtain flow and water level forecasts for the river reach between Fredericton and Saint John.

The five day forecasts produced in this way are issued daily before noon, by telecopier to N.B.E.P.C., the Emergency

Measures Organization, Emergency Planning Canada, Inland Waters Directorate, Halifax, and Atmospheric Environment Service in Fredericton and Bedford, N.S.

After the flows at Mactaquac Dam exceed or are forecast to exceed 80,000 c.f.s. (2,266 cms) three day forecasts only are provided to the New Brunswick Information Service (N.B.I.S.) for distribution to the media and the National Weather Service (N.W.S.) at Portland, Maine is kept advised of critical situations as they develop on the U.S. side of the border. When river flows at Mactaquac are between 80,000 cfs (2266 cms) and 200,000 cfs (5666 cms), which is before significant flooding starts to occur at Fredericton and downstream, all models are run once a day and routine releases are made to the media, by telephone and by use of a taped message (code-a-phone), available to the public by 7:30 a.m. based on a review of the previous day's forecast and the early morning update on the river situation. The forecast is released through N.B.I.S. before noon and verbally to radio and T.V. stations and via the code-a-phones.

When flows exceed the critical value of about 200,000 cfs runs are made and forecasts issued twice a day - at 11:45 a.m. and 10:45 p.m., with a verbal update at 7:00 a.m.

In extreme situations when forecasts indicate that serious flooding will occur, a third run will be made in the early morning with a full forecast issued by 6:45 a.m. and as in the previous case, at 11:45 a.m. and 10:45 p.m.

Staff requirements at the Centre vary considerably depending on the season and the flow or flood situation. For the part of the year other than the spring freshet period, regular staff consists of the Director, (part time only) the Forecast Engineer and the Forecast Technician. Two meteorological technicains man the Met Centre continuously throughout the year providing special weather products to various users such as the Dept. of Natural Resources for forest fire purposes, the Dept. of Transportation for weather related traffic purposes, the New Brunswick Electric Power Commission for transmission line and distribution concerns and for load forecasting. Throughout the year they monitor weather continually for the River Forecast Centre and are completely dedicated to it during the spring freshet period or at other times when forecasts indicate severe flood producing weather patterns.

During the spring and particularly when flooding is occurring or is imminent, the Met Technicains provide weather briefings twice a day and more often if required, to Centre staff and by means of conference calls and speaker phones to audiences at E.M.O., N.B.E.P.C. and others.

During the winter and early spring, when the rivers are ice covered, the local office of the Water Survey of Canada (W.S.C.) provide technical support to the Centre and monitor river flow conditions and carry out "backwater cutting" under ice to determine true discharge amounts at several locations along the River.

This service is discontinued after the rivers and streams are ice free but the W.S.C. continue to operate and service the telemark and D.C.P. network for the Centre.

During the period mid March (when the Centre commences daily operations) to late May, the N.B.E.P.C. provide a technician as required to assist in the daily routine. When the Centre commences to produce three forecasts a day a second Technician is supplied by N.B.E.P.C. These technicians are given an opportunity to update their skills in early training sessions. They have been associated with the Centre in this manner for a number of years.

FINANCES AND BUDGETS

The original Federal-Provincial Agreement Respecting Flood Forecasting was signed on August 30, 1977 with a termination date of March 31, 1982. The financial commitment was a total of $600,000 - $300,000 from each party. The amended agreement signed on July 16, 1981 has a termination date of March 31, 1987 and a total commitment of $1,400,000 or $700,000 from each party over the total 10 year period from August 30, 1977 to March 31, 1987. As of March 31, 1983, a total of $664,000 had been expended. The 83-84 shareable expenditures will amount to about $150,000 to bring the total to $814,000 by March 31, 1984.

Under an agreement between N.B.E.P.C. and N.B.D.O.E. the contribution from the former amounts to 1/6 of the total or about $136,000 to the end of March, 1984. The N.B.E.P.C.

contribution this fiscal year will be about $25,000.

Under separate agreement, N.B.E.P.C. contributes an additional $1,200 a year to help defray the cost of the teletypes and the facsimile recorder installed in the Met. Centre. The Dept. of Natural Resources contribute $3,300 annually for this same purpose.

The periodic "flow" forecasting service provided to the Energy Control Center is charged for at the rate of $230 per forecast for those forecasts carried out especially for this purpose. No charges are made for forecasts which the Centre would normally be making for other purposes such as floods, special heavy rain events (hurricanes, ice jams, etc.) or for normal monitoring for model updating purposes. Last year the total charges for this service amounted to $6,670.

The N.B. Dept. of the Environment serves as "banker" for this program. All shareable costs of operating the Centre are initially funded by it and then recovered periodically by invoicing Environment Canada, the New Brunswick Electric Power Commission and the N.B. Dept. of Natural Resources.

The expenditures noted above are those which are shareable under the Federal-Provincial Agreement. Other costs are incurred by the various agencies which support the program.

Examples of the support provided by these agencies, in addition to participation on various committees, is indicated in the following tabulation:

N.B.D.O.E. - Forecast Engineer - wages and expenses
- Met. Technicians - wages and expenses (except overtime which is a shareable expense)
- Snow surveys and ice observations
- Office space and support services

N.B.E.P.C. - 2 Forecast Technicians - during the spring freshet period (except overtime which is a shareable expense).

- Engineering and computer programming support as required.

- Snow Surveys and ice observations.

I.W.D. - Technician for river discharge determinations under ice conditions.

- Special studies and investigations.

A.E.S. - Special "flood messages".

- Special studies - i.e. weather related computer programs.

CONCLUSIONS

The forecasting program described has particular characteristics from a management point of view because it is jointly sponsored by Federal and Provincial agencies under an agreement. This requires a committee form of management to ensure that the various interests are represented. The vested interests of several Provincial agencies have also led to further involvement with committees and the international character of the basin creates U.S. and State of Maine interests which have been resolved by the formation of committees with representation from the various agencies involved on both sides of the border.

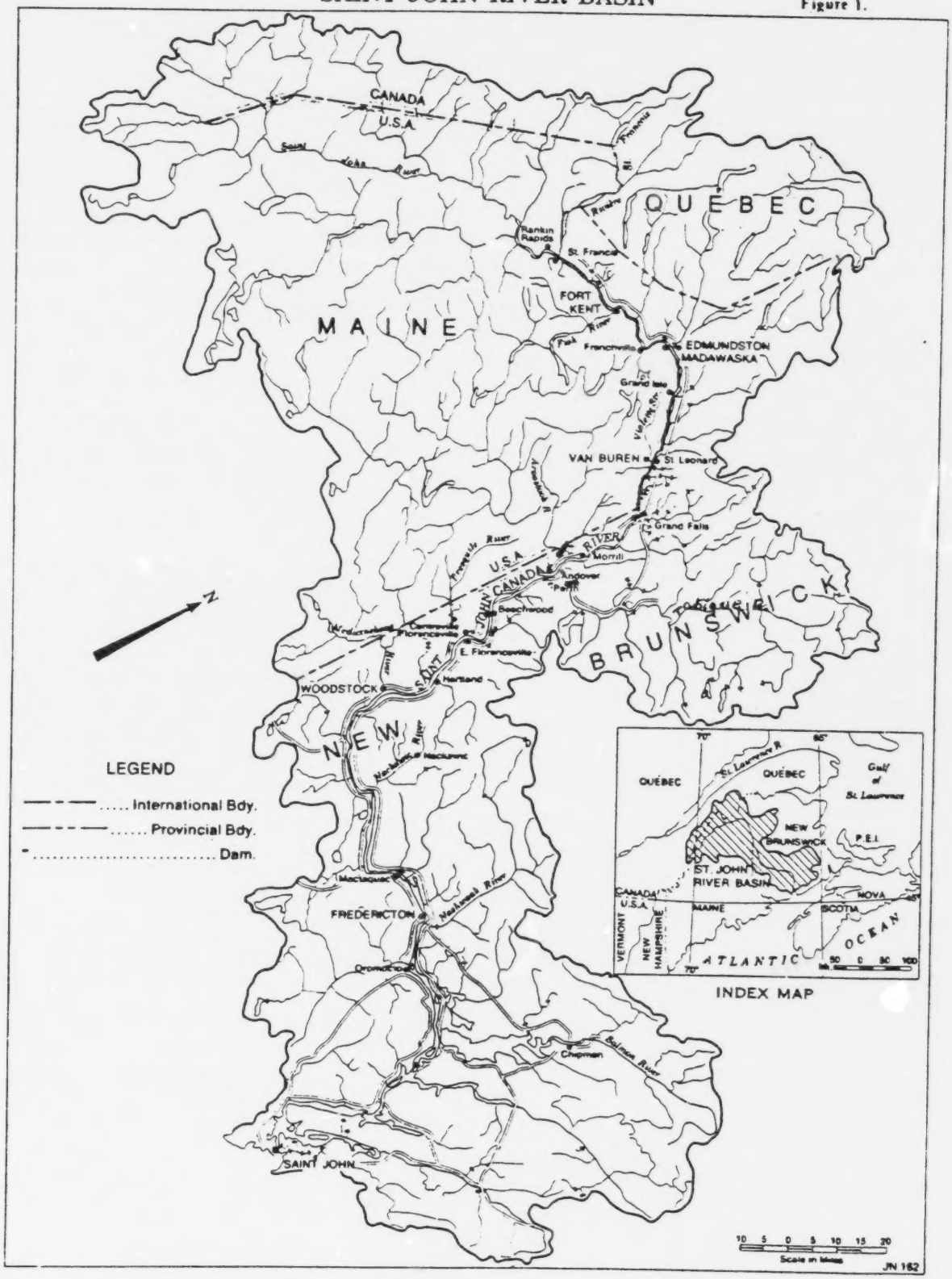
Advantage has been taken over a long period of time by the flood forecasting group of various peripheral systems and services. This cooperative effort may be somewhat unique and lends itself to a committee-type structure to involve those agencies providing the service with the forecasting functions.

The operational structure is perhaps more conventional although the fact that full time daily operation is carried on essentially for only three months of the year and that temporary technical support is provided by a separate agency may also be unique.

It is hoped that this presentation, although it does not compare various approaches to management and organization of flood forecasting systems, will serve to stimulate discussion with regard to the several components identified.

SAINT JOHN RIVER BASIN

Figure 1.



PART III

LIST OF PARTICIPANTS

PARTIE III

LISTE DES PARTICIPANTS

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Meteorological Input to Forecasting / Apport de la météorologie

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Nabil Elhadi, Serge Bouchard, Robert Fox, Stan Siok, Howard Ng, Hugh Whiteley

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WORKING GROUP / GROUPE DE TRAVAIL - NO. 2
Hydrometric Input to Forecasting / Apport de l'hydrométrie

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